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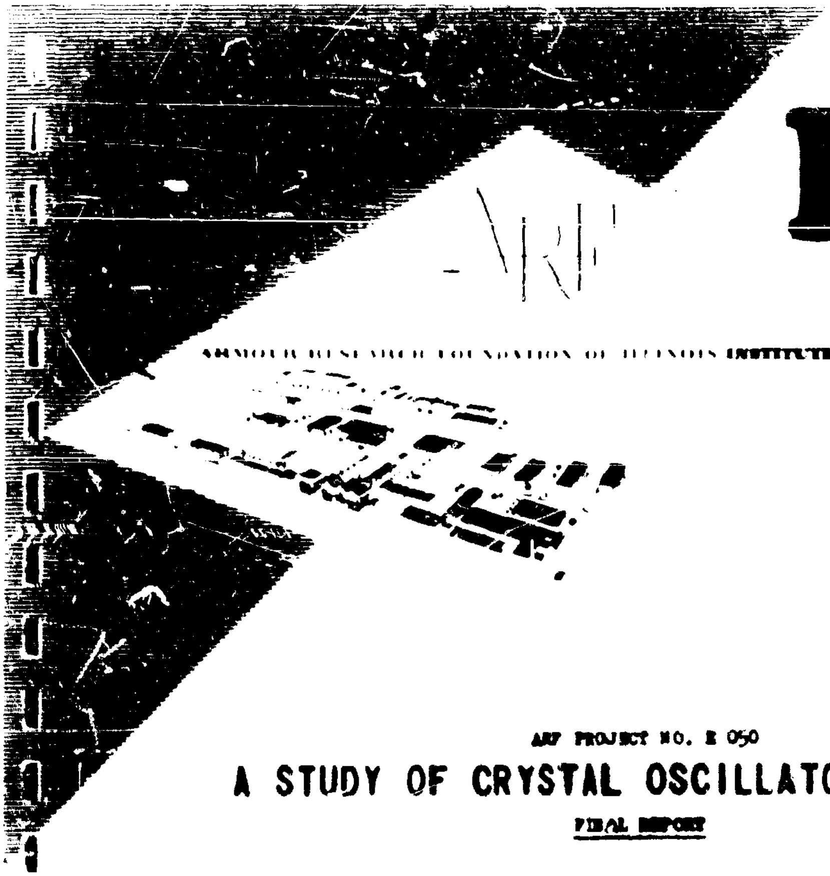

ARF

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

ARF PROJECT NO. E 050

A STUDY OF CRYSTAL OSCILLATOR CIRCUITS

FINAL REPORT

15 May 1955 - 14 August 1957

Signal Corps Contract No. DA36-039 sc-[illegible]

Department of the Army Project No. 3-[illegible]

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U. S. Army

Signal Engineering Laboratories

Fort Monmouth, New Jersey

RESEARCH FOR INDUSTRY

ARF PROJECT NO. E [illegible]

A STUDY OF CRYSTAL OSCILLATOR CIRCUITS

Final Report

14 August 1957

Signal Corps Contract No. DA-36-039-sc-[illegible]
Department of the Army Project No. 3-2[illegible]-02-072
Signal Corps Project No. 367B

Technical Requirements:

As Per PR and C [illegible]-ELS [illegible]
dated 27 July 1954

and PR and C 56-ELS [illegible]
dated 3 February 1956

This study was directed toward the development of usable circuits and sound techniques of operation of VHF crystal oscillators and to the development of a method of design to be used in the frequency range of 0.8 to 150 mc. The feasibility of circuit design and performance at frequencies up to [illegible] mc was also to be investigated.

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A STUDY OF CRYSTAL OSCILLATOR CIRCUITS

Signal Corps Contract No. DA36-039-sc-64609

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PURPOSE

The purpose of this project was to develop usable circuits and sound techniques of operation for VHF crystal oscillators and to develop a method for the design of crystal oscillator circuits to be used in the frequency range of 0.8 to 150 mc. This design method is applicable for use by designers of electronic equipment which requires the use of crystal oscillators for frequency control.

The program was carried out in several phases; a study of the applicable literature, selection of circuits showing the most desirable performance characteristics, experimental verification of circuit performance, selection of circuits for detailed design studies, determination of operation for a wide variation in component values, and development of a design method for VHF crystal oscillators.

Circuit design data was also obtained for oscillators in the 10 to 75 mc range and combined with that available for antiresonant circuits in the range 0.8 to 20 mc. This was then coordinated to yield a method of design for crystal oscillators over the complete 0.8 to 150 mc frequency range. Feasibility of circuit operation at frequencies up to 200 mc was also investigated.

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ABSTRACT

A complete design method for crystal oscillators operating over the 0.8 to 150 mc frequency range is presented. Investigation of a variety of series resonant oscillator circuits is described in detail, covering various aspects of performance characteristics. The criteria used to select the Grounded Grid and Cathode Coupled circuits for detailed investigation are given. In addition, the reasons for selecting the Capacitance Transformer Coupled oscillator, a circuit developed during the contract period for use with subminiature tubes, are discussed. Loop gain equations are developed for several circuits and relative merits of the circuits are analyzed by use of the equations, supported by experimental results.

The development of the design method is reviewed, showing the resulting establishment of reference circuits for each oscillator type, capable of operating over the frequency range and plate supply voltages, and having desirable performance characteristics. By varying circuit component and parameter values, measurements of the resulting performance changes were obtained and plotted. By normalizing these graphs with respect to the reference circuit component values, a set of curves were obtained which could be used to predict the performance of an oscillator over a wide range of operating conditions.

Finally, a complete design method, in the form of graphs and tables, is presented for the two series resonant oscillators operating in the 10 to 150 mc frequency range. Design information is also given for the

Grounded Grid and Capacitance Transformer Coupled oscillators, which operate with subminiature directly heated cathode tubes, over the frequency range of 75 to 150 mc. Three antiresonant circuits, the Colpitts (Grounded Plate Pierce), the Electron Coupled Colpitts, and the Miller oscillators, have been investigated. Together with information already available from a previous contract with Wright Air Development Center on Colpitts oscillators, a design method for these circuits is presented to cover the 0.8 to 20.0 mc frequency range. Complete circuit descriptions, construction details, tuning procedure, design examples, and performance information (which includes frequency stability, frequency-temperature effects, and harmonic content) are given.

Performance of the two series resonant circuits at frequencies up to 200 mc is included. However, design information is not established above 150 mc.

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PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

The following information applies from 15 May 1955 to 14 August 1957:

PUBLICATIONS: A paper, entitled "The Effects on the Frequency of VHF Crystal Oscillators Resulting From the Use of a Compensating Inductance", by H. E. Gruen and A. O. Plait, was presented to the A.I.E.E. 1956 Technical Papers Contest on 3 April 1956, and was awarded Second Prize.

LECTURES: Papers were presented at both the Tenth and Eleventh Frequency Control Symposia by H. E. Gruen, at Asbury Park, New Jersey. The first, entitled "Design Data for Crystal Oscillators", was given on 16 May 1956. The second, entitled "Design Criteria for Vacuum Tube Crystal Oscillators, was given on 9 May 1957.

REPORTS: None

CONFERENCES: The following dates and places refer to project conferences held during the course of this program. Minutes for each meeting were prepared and submitted to the U. S. Army Signal Engineering Laboratories and are on file for reference.

Date	Place
14, 15 June 1955	ARF
6 October 1955	ARF
5, 6 January 1956	USASEL
23 March 1956	USASEL
1, 2 August 1956	ARF
30 October 1956	USASEL
12, 13 February 1957	ARF
22 March 1957	USASEL
26 June 1957	ARF

TABLE OF ABBREVIATIONS AND SYMBOLS

A	Voltage Amplification Factor
B+	Plate Supply Voltage
C_c	Coupling Capacitor
CC	Cathode Coupled oscillator
C_f	Feedback Capacitor
C_{gc}	Grid-to-Cathode Capacitor in the Cathode Follower Stage (CC oscillator)
C_o	Crystal Shunt Capacitance
c_p	Plate Capacitance
C_p	Plate Capacitor
CTC	Capacitance Transformer Coupled oscillator
C_t	Total Crystal Load Capacity ($= C_1 + C_2C_3/(C_2 + C_3) = 32$ mmfd)
C_1	Grid-to-Ground Capacity Across Crystal, or Series Arm Crystal Capacitance
C_2	Grid-to-Cathode Capacity
C_3	Cathode-to-Ground Capacity
E_c	Grid-to-Cathode Bias Voltage (dc)
ECC	Electron Coupled Colpitts oscillator
e_f	Filament Voltage
e_g	rms Grid-to-Cathode Voltage
E_g	Peak ac Grid-to-Cathode Voltage Swing ($=\sqrt{2}e_g$)
e_o	rms Output Voltage
e_x	rms Crystal Voltage
f	Frequency
f_a	Crystal Antiresonant Frequency
f_b	Oscillator Operating Frequency Resulting From a Change in B+ from normal

f_f	Oscillator Operating Frequency Resulting from a Change in e_f from normal
f_n	Nominal Crystal Frequency
f_o	Oscillator Operating Frequency
f_r	Crystal Series Resonant Frequency
f_s	Crystal Series Arm Resonant Frequency
G	Amplifier, Stage or Loop Gain
GG	Grounded Grid oscillator
g_m	Tube Transconductance
i_p	Plate Current
k	Inductive Coupling Coefficient
K	10^3
L_e	Effective Antiresonant Inductance of Crystal
L_k	Cathode Tuning Inductance
L_p	Plate Tuning Inductance
L_s	Inductance of Transformer Secondary Winding
L_{sf}	Crystal Series Compensating Inductance
L_x	Crystal Shunt Compensating Inductance
L_1	Leakage Inductance of Transformer or Crystal Series Arm Inductance
m	10^{-3}
M	10^6
mc	Megacycles per Second
mw	Milliwatts
n	Order of Crystal Overtone
N	Transformer Turns Ratio
N'	Normalized Circuit Performance Parameter
N'_R	Normalized Circuit Component Value

P_o	Power Output
ppm	Parts Per Million
P_r	Ratio of P_o to P_x
P_x	Crystal Driving Power
Q	Coil Quality Factor ($= \omega L/R$)
r	Ratio of C_o to C_1 of crystal
R_e	Resistance of Crystal at Antiresonance
r_g	Equivalent ac Grid-to-Cathode Resistance of a Tube
R_g	Grid Bias Resistor
R_{gc}	R_g of a Cathode Follower Stage
R_{gg}	R_g of a Grounded Grid Stage
R_k	Cathode Bias Resistor
R_{kc}	R_k of a Cathode Follower Stage
R_{kg}	R_k of a Grounded Grid Stage
r_L	ac Load Resistance
R_L	Load Resistor
r_p	Plate Resistance of a Tube
R_1	Series Arm Resistance of Crystal
T	Number of Coil Turns
X_c	Capacitive Reactance ($= 1/\omega C$)
X_L	Inductive Reactance ($= \omega L$)
Z_L	Load Impedance
Δf_b	Stability Figure for Changes in B+ ($= f_o - f_b)/f_n$ in ppm)
Δf_f	Stability Figure for Changes in e_f ($= (f_o - f_f)/f_n$ in ppm)
Δf_s	Oscillator Frequency Correlation Figure ($= f_o - f_s)/f_n$ in ppm)

ΔT	Tap Point on Transformer, in turns
μ	10^{-6}
$\mu\mu$	10^{-12}
ω	Angular Frequency ($= 2\pi f$ radians per second)

A STUDY OF CRYSTAL OSCILLATOR CIRCUITS

I. INTRODUCTION

This is the final report on ARF Project No. E-050, entitled "A Study of Crystal Oscillator Circuits". This program was conducted for the Frequency Control Branch of the U. S. Army Signal Engineering Laboratories, under Contract No. DA36-039-sc-64609. The initial contract dates were from 15 May 1955 to 14 May 1956. This was later extended to 14 August 1957.

The need for precise frequency control in modern military communications equipment and stable sources for UHF and microwave frequency stabilization has led to considerable investigation of piezoelectric quartz crystals and their application in practical oscillator circuits. With the successful production of thickness-shear mode, high frequency, series-resonant crystal units, it has become necessary that the designer of electronic equipment utilize these units in practical oscillator circuits, thus eliminating frequency multiplier stages which require additional power and space. An important additional requirement of these circuits is that they remain stable for a wide variety of operating conditions.

It has been the purpose of this program to develop usable circuits and sound techniques of operation of the VHF crystal oscillators, and to develop a method of design of crystal oscillators to be used in the frequency range of 0.8 to 150 mc. A straightforward design approach for circuits of this type should prove extremely useful to designers of electronic equipment requiring crystal oscillators for frequency control.

The initial technical requirements called for the development of a design methode for series resonant oscillators operating in the 75 to 150 mc range. Later, the contract was revised to include the development of design information for the chosen circuits over the 10 to 150 mc range. In addition, performance data for antiresonant oscillators, covering the range from 0.8 to 20 mc, was to be incorporated into the overall program to provide oscillator design data for the entire range of 0.8 to 150 mc. Data for the antiresonant circuits was taken primarly from the results of a previous program, but was rechecked and extended to cover the necessary frequency range.

The design of practical crystal oscillators has been approached by many designers on a cut-and -try basis. Mathematical design procedures, although possible if all circuit characteristics are known, are so complex that their use is not practical. The analysis is often simplified by making various assumptions to the point where little quantitative information remains. The information presented here correlated the two approaches. A simple linear loop gain analysis yielded qualitative information which was supplemented by performance measurements to provide quantative information for the design graphs.

A number of crystal oscillators were investigated to determine those circuits having the most desirable performance characteristics. The selected circuits, which were the Grounded Grid and the Cathode Coupled series resonant oscillators and the Colpitts (Grounded Plate Pierce), Electron Coupled Colpitts, and the Miller anti-resonant circuits were then analyzed to determine specific characteristics over a wide range of operating conditions. A single circuit Configuration for each oscillator type was chosen to operate over prescribed frequency ranges. By varying circuit components through a range of values and measuring the resultant performance, a complete set of design data was obtained.

The design display for the series resonant circuits resulted from the generalization of performance characteristics over the range of frequencies and plate supply voltages. Once the performance of the circuits was determined, output voltage, output power, crystal power, and circuit component variation characteristics were normalized with respect to the recommended circuit values.

The following sections of this report discuss the results of the literature survey and performance comparison upon which the selection of the most desirable circuits is based, preliminary design information, and the design format development. The final section details the design method and provides design examples of each circuit type.

In general, output voltage predictions are within 20 percent of the values indicated for specific oscillator circuit designs. Crystal drive prediction accuracy is within 30 percent. This latter figure is based on measurements of crystal voltage and assumed resistive operation of the crystal.

Additional studies of the selected series resonant circuits were made to determine the feasibility of their use up to 200 mc. Performance measurements revealed lower output and a more critical tuning procedure.

II. SURVEY AND SELECTION OF CIRCUITS

The program for selection of the best available circuits and development of operational techniques in the 75 to 150 mc frequency range was initiated with a survey of the literature to determine the circuits applicable for use at these frequencies. This initial survey revealed a total of twelve circuit types which are known to have been used or investigated for use at frequencies above 50 mc. The majority of these are series resonant types. Two are antiresonant types and one utilizes an impedance inverting network to transform the low series-resonant impedance to a high impedance for operation in the conventional antiresonant circuits. Basic schematics of these circuits are shown in Figs. 1 through 12.

The Cathode Coupled circuit shown in Fig. 1 consists of a grounded grid amplifier driving a cathode follower. The crystal operates at series resonance between the two cathodes, and forms the upper arm of a voltage divider. The lower arm consists of the amplifier input impedance where the feedback voltage is developed. If all stray capacities are compensated, and the plate tank is tuned to resonance at the operating frequency, the crystal will operate at series resonance. When this circuit is tuned for maximum voltage output or peak grid current the operating frequency increases with increasing "Q" and impedance of the plate tank, and decreases with increasing capacitive phase shift in the cathode circuits. As a result, at frequencies in the range of interest, operation will normally be below series resonance with uncompensated cathode capacities since high impedance tank circuits are difficult to obtain in the average tuned circuit above 75 mc. The cathode follower can be designed to provide zero-phase shift by proper balance of the grid-to-cathode and cathode-to-ground

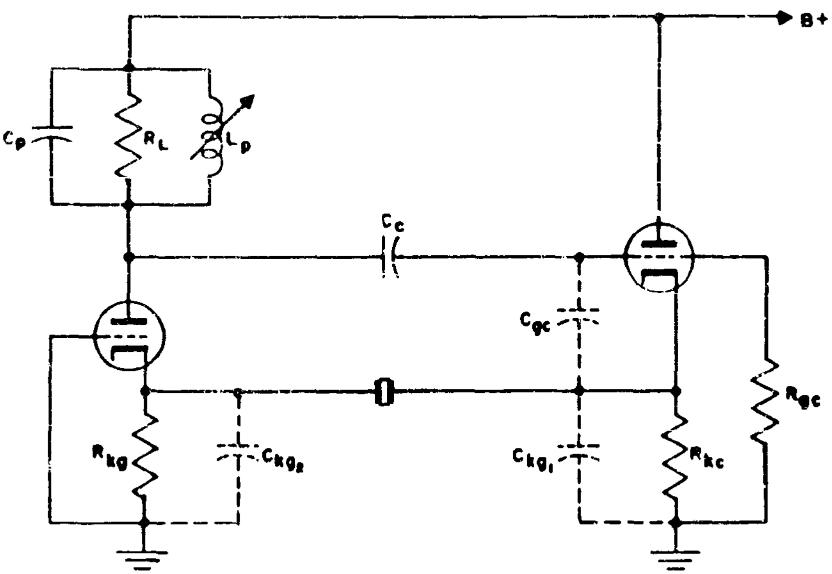


FIG. 1—CATHODE COUPLED OSCILLATOR.

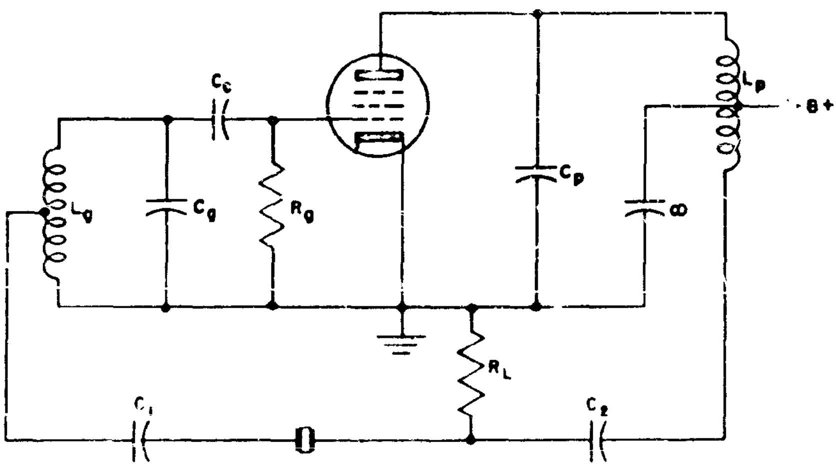


FIG. 2—TRANSFORMER COUPLED OSCILLATOR.

capacities. This circuit provides moderate power output at low crystal drive levels and is a relatively simple circuit to adjust at frequencies up to 150 mc. The greatest disadvantage of this type is that two tubes are required, and even though twin triodes are available the greater power requirement is a distinct disadvantage.

The Transformer Coupled oscillator of Fig. 2 consists of a grounded cathode amplifier in a tuned-plate tuned-grid arrangement. A pentode having low grid-to-plate capacity is required to prevent oscillation when the crystal is removed. If a triode is used neutralization is required. Feedback voltage is obtained from a tap on the plate coil and is fed to the grid transformer through the crystal. Either the plate or grid transformer must provide a 180° phase shift to assure oscillation. If the plate and grid circuits are properly tuned and the leakage inductances of the two transformers are tuned by C_1 and C_2, operation will be at the series resonant frequency of the crystal. Previous investigations[2] of this circuit indicate that broadband (12 to 20 mc. bandwidth) operation can be obtained on a plug-in basis with this circuit, however, this results in operating the crystal off resonance. Operating frequency is off resonance by as much as 28 ppm for a frequency differing by 10 percent from design center. The circuit is useful at frequencies up to 150 mc; however, adjustment is relatively difficult. High levels of power output are obtainable but at the expense of high crystal drive level.

The Grounded Grid oscillator circuit shown in Fig. 3 consists of a grounded grid amplifier, whose driving signal is obtained from a tap on the autotransformer located in the plate circuit. Operation is at series resonance of the crystal if the plate and cathode circuits are properly

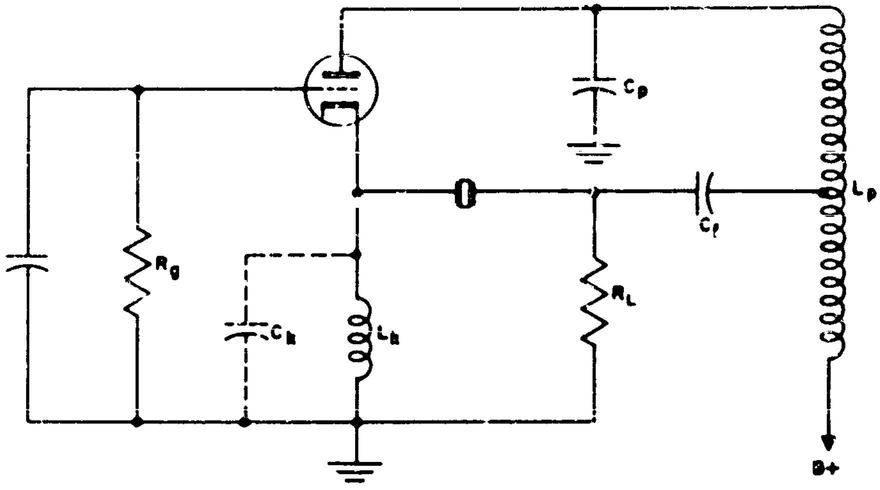


FIG. 3 — GROUNDED GRID OSCILLATOR.

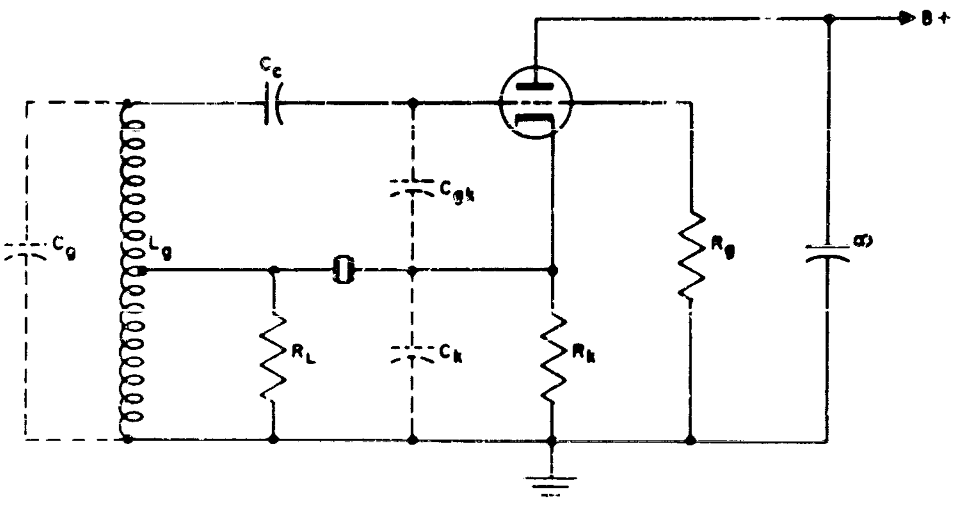


FIG. 4 — GROUNDED PLATE OSCILLATOR

tuned and if the leakage inductance is resonated with C_1. The circuit is relatively simple to adjust in comparison to the transformer coupled circuit, the plug-in bandwidth is somewhat narrower, and the ratio of power output to crystal drive is only slightly less than that obtained with the transformer coupled circuit.

In the grounded plate circuit of Fig. 4 the tube is connected as a cathode follower which drives the crystal at series resonance. The grid driving voltage is obtained from a step-up transformer in the grid circuit. With the exception that this circuit is readily adaptable to electron coupled operation it offers no distinct advantage over the transformer coupled or grounded grid circuits.

The circuit of Fig. 5 is the well known circuit used in the TS-683 and other Crystal Impedance meters. The circuit consists of two impedance transforming networks to match the high level grid and plate impedances to the low value of the crystal network. This circuit is also known as a line coupled oscillator, the two impedance transforming networks being considered as transmission line sections. This circuit is very useful for determining crystal resistance by the substitution method, but its low power output and complicated circuit limit its use as a source of high frequency power.

The Capacitance Bridge circuit is shown in Fig. 6. This circuit has been described in detail by Mason and Fair[3]. It performs well in the 75 to 200 mc range when properly adjusted, but its complicated circuit and tend[illegible] to free run unless adjusted very carefully do not warrant its use in military equipment.

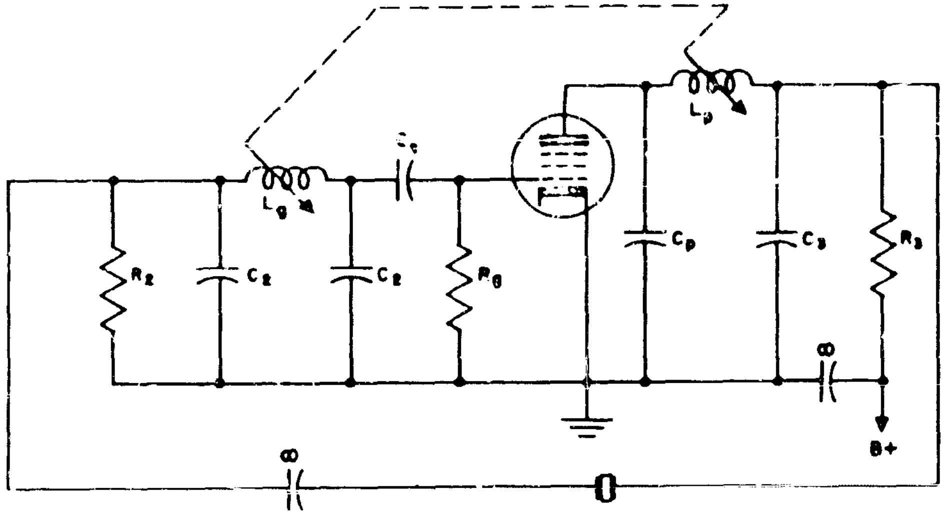


FIG. 5—CI METER OSCILLATOR.

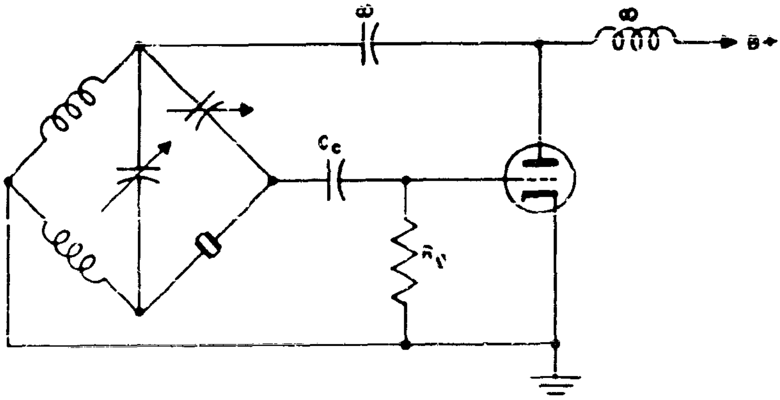


FIG 6—CAPACITANCE BRIDGE OSCILLATOR

The Bridged "T" Oscillator circuit shown in Fig. 7 has also been investigated for use in the VHF range[4]. This circuit when properly adjusted operates the crystal at approximately series resonance. With the resulting low impedance path through the crystal this circuit configuration resembles that of the familiar Colpitts.

The circuit of Fig. 8 shows the Colpitts or Grounded Plate Pierce, antiresonant circuit. This circuit is in wide use in military equipments at lower frequencies. For high frequency operation the cathode choke is chosen such that the cathode-to-ground impedance is capacitive only in the range of the desired overtone. For lower than the desired order of overtone this branch is inductive and proper phase relations do not exist. Previous investigators have been reluctant to consider an antiresonant circuit for high frequency overtone operation due mainly to the low impedance level developed by typical high frequency crystals at antiresonance. This type of circuit does offer certain advantages such as circuit simplicity and ease of adjustment and may be used successfully with crystals of extremely high quality.

Fig. 9 shows the circuit of the Impedance Inverting Pierce circuit. Circuits of this type utilize an impedance inverting network to transform the low series resonant impedance to a higher impedance value for use in the conventional antiresonant circuits such as the Pierce and Miller. These circuits are relatively simple to adjust at one frequency but operate only over a very narrow bandwidth. The power output and efficiency are low and the circuit does not perform well above 100 mc.

The Lister[5] circuit of Fig. 10 utilizes the crystal in an antiresonant arrangement in the grid circuit. The grid circuit coil is adjusted to present an inductive reactance to the crystal. The circuit then operates

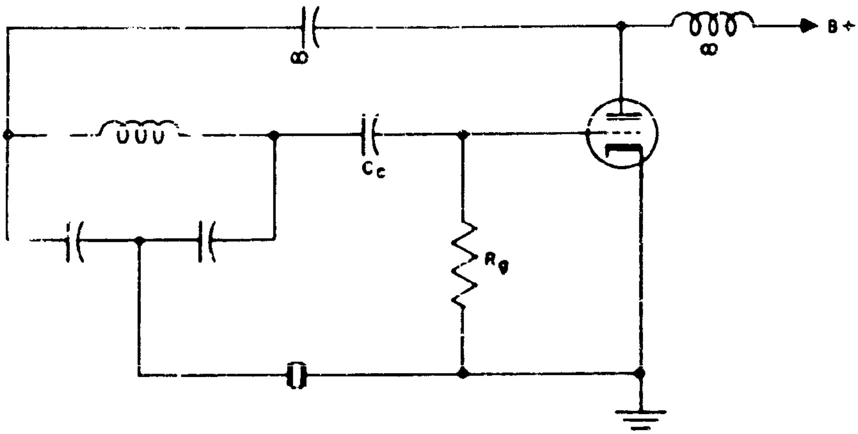


FIG. 7—BRIDGED "T" OSCILLATOR

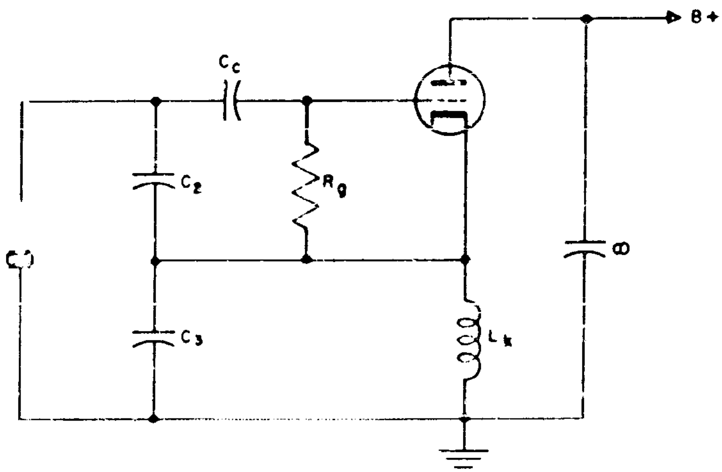


FIG 8—COLPITTS CRYSTAL OSCILLATOR

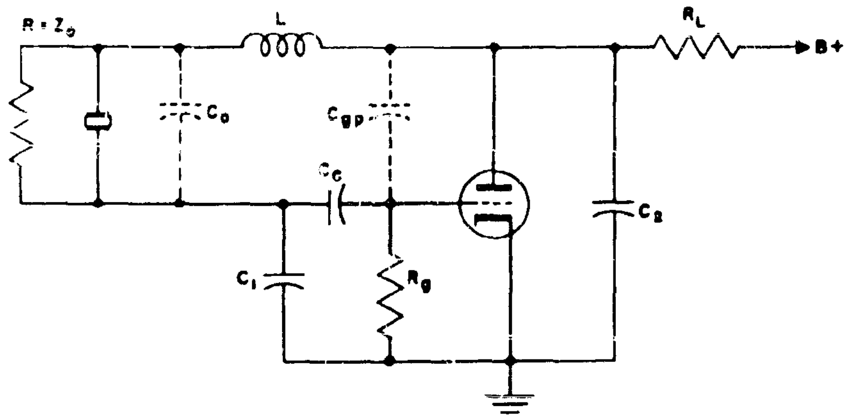


FIG. 9—IMPEDANCE INVERTING PIERCE OSCILLATOR

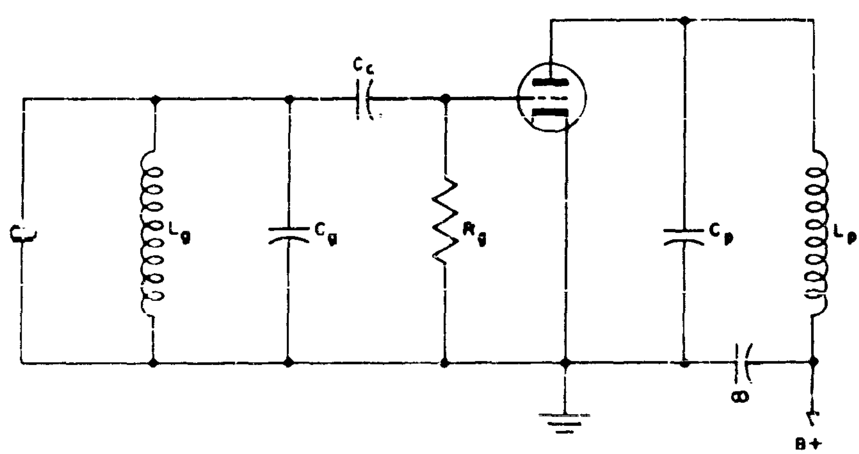


FIG. 10—LISTER CRYSTAL OSCILLATOR.

as a tuned-grid tuned-plate oscillator with the crystal operating in the capacitive reactance region. The operating frequency is thus below the series resonance of the crystal. Reasonable values of output are produced but adjustment is difficult, and unless done very carefully, uncontrolled oscillations close to the desired frequency will be obtained.

Two series mode circuits suitable for use with high resistance crystals have been described by Heegner[6]. These are the Transitron and Feedback crystal oscillators whose circuits are shown in Figs. 11 and 12. These circuits can be made to operate at single frequencies as high as 150 mc when carefully designed and adjusted. However, only when extremely high resistance crystals are used do these two circuits offer distinct advantages over the more straightforward types.

Table I summarizes the more important characteristics of these twelve circuits. From this table and the preceding discussion, selection of the most promising circuits for further study was made. On the basis of circuit efficiency and ease of adjustment reported in the literature three circuits were selected for further immediate investigation for general use. These were the Cathode Coupled, Transformer Coupled, and Grounded Grid circuits. Additional information was obtained on their performance to determine which of these should receive the most extensive development during the remainder of the program. All have distinct advantages for certain applications. The Bridged "T" and Colpitts circuits were also subjected to further experimental investigation before final evaluation was made.

The Grounded Grid circuit provided satisfactory operation at 72 mc during initial investigation. Ratios of power output to crystal drive of 20 and 30 to 1 were obtained. The circuit is relatively simple to design

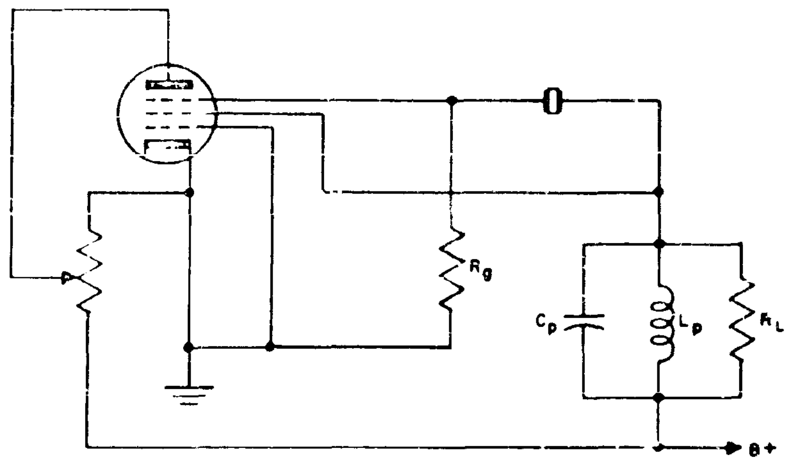


FIG. 11—TRANSITRON CRYSTAL OSCILLATOR.

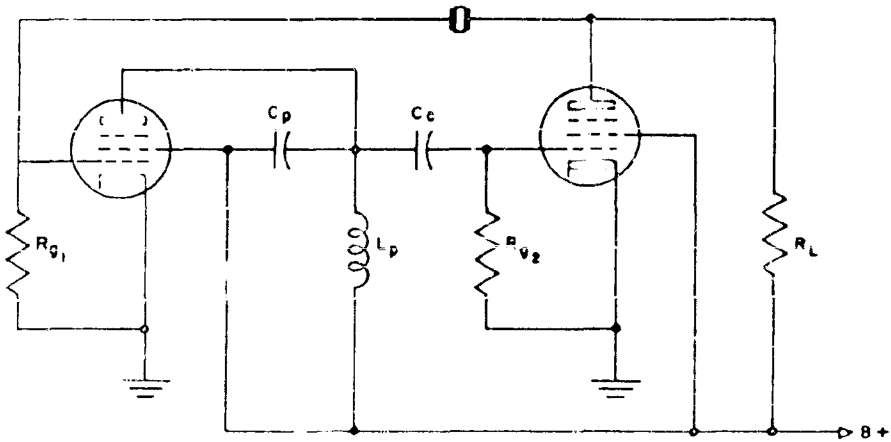


FIG 12—FEEDBACK CRYSTAL OSCILLATOR.

Circuit Type	Power Output	Drive Level	Bandwidth (Untuned)	Frequency Range	Ease of Adjustment
Cathode Coupled	Medium	Low	5-10 mc	to 150 mc	Simple
Transformer Coupled	High	Medium	12-20 mc	20-150 mc	Difficult
Grounded Grid	Medium	Low	12-15 mc	20-150 mc	Simple
Grounded Plate	Medium	Medium	10 mc	20-125 mc	Difficult
C. I. Meter	Low	Variable	-	to 120 mc	Relatively Difficult
Capacitance Bridge	-	-	Narrow	75-200 mc	Very Difficult
Bridged "T"	High	Medium	-	-	-
Colpitts Antiresonant	Medium	Low	-	-	Simple
Impedance Inverting	Low	Low	Very Narrow	to 100 mc	Simple at one Freq.
Lister	High	Medium	Narrow	to 150 mc	Very Difficult
Transitron (Heegner)	Low	Low	Narrow	to 150 mc	Relatively Difficult
Feedback (Heegner)	-	-	-	-	Difficult

TABLE I - COMPARISON OF HIGH FREQUENCY CRYSTAL OSCILLATOR CIRCUITS and adjustment is straightforward. Frequency of operation is somewhat below the crystal series resonant frequency unless all tuning, including that of the transformer leakage inductance, is carefully done. However, operation at series resonance is very easy to obtain if the oscillator is operated only at one frequency.

The Cathode Coupled circuit is the simplest to adjust of any high frequency circuit. The ratio of power output to crystal drive is lower for this circuit than for other high frequency circuits, and the requirement of two tube sections is a decided disadvantage. However, the extreme circuit simplicity and straightforward operation warrant its use in many applications.

Preliminary investigations of the transformer coupled circuit have shown it to be very difficult to adjust for proper operation, and thus to be too critical for most military applications. Although previous investigations indicated good operation with this circuit at frequencies of 50 to 60 mc, comparable results were not obtained at 72 mc.

Further investigation of the selected circuits was made at specific operating frequencies in the range of 75 to 150 mc. Specific attention was given to comparative data obtained by means of evaluation of the circuits with regard to five parameters. These parameters are:

a. Crystal Driving Power; computed from the voltage measured across the crystal and the series resonant crystal resistance, as measured in Crystal Impedance Meter.

b. Output Power; computed from the measured output voltage across a known load resistance.

c. Power Ratio; the ratio of output power to crystal driving power.

d. $\Delta f_s = f_s - f_o$; expressed in parts per million of the nominal crystal frequency, where f_s is determined by use of the Crystal Impedance Meter and f_o is the operating frequency when the circuit is tuned for maximum output.

e. $\Delta f_b = f_o - f_b$; expressed in parts per million of the nominal crystal frequency, where f_b is the frequency obtained when the plate supply voltage has been changed by ten percent, the circuit not being retuned.

The values of the parameters resulting from the tests made on the various circuits were compiled and averages determined. This information is presented in Tables II through XIV below.

A. <u>Cathode Coupled Oscillator</u>

The circuit of Fig. 13 is typical of the Cathode Coupled circuits used for comparative performance tests. Table II indicates the parameter values for selected crystals operated at various plate supply voltage levels (B+), at 75 mc. Tables III, IV, and V show typical operation at 105, 135 and 150 mc respectively. Some performance information was also obtained at 120 mc but is not indicated here because of its similarity to the performance at 135 mc.

The data shown in Table II, for operation at 75 mc, resulted from use of a circuit having an untuned cathode circuit in the grounded grid stage. The circuit was completed with a 1000 ohm cathode resistor. When this cathode circuit is tuned as shown in Fig. 3, performance is comparable to that obtained at the higher frequencies. It was determined from this information that the cathode circuit should be tuned to obtain reasonable performance at frequencies at 75 mc and above.

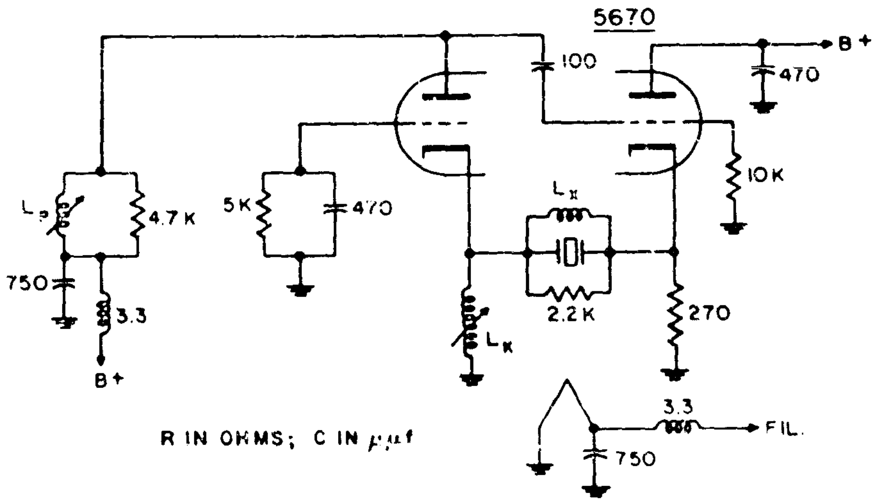


FIG. 13. CATHODE-COUPLED OSCILLATOR

Crystal	E_b volts	P_x mw	P_o mw	P_o/P_x -	Δf_a ppm	Δf_b ppm
#703	100	0.7	1.3	1.9	-6.5	-
R_x=22 ohms	125	1.2	3.4	2.8	-8.6	2.0
	150	2.6	5.9	2.3	-6.0	-
#707	100	0.2	1.1	5.5	-12.5	-
R_x=51 ohms	125	0.6	2.6	4.3	-11.1	1.5
	150	1.5	5.3	3.5	- 8.0	-

TABLE II - CATHODE COUPLED OSCILLATOR PERFORMANCE AT 75 mc.

Crystal	E_b volts	P_x mw	P_o mw	P_o/P_x -	Δf_a ppm	Δf_b ppm
#830	75	1.0	2.9	3.0	-8.5	-
R_x=40 ohms	100	2.3	7.7	3.4	-3.8	2.2
	125	4.9	16.6	3.4	-0.6	-
#828	75	1.0	3.5	3.5	-5.5	-
R_x=60 ohms	100	2.9	8.5	2.9	-3.8	4.1
	125	6.3	17.7	2.8	-1.0	-

TABLE III - CATHODE COUPLED OSCILLATOR PERFORMANCE AT [illegible] mc.

Crystal	B+ volts	P_x mw	P_e mw	P_e/P_x -	Δf_s ppm	Δf_b ppm
#832	100	0.4	5.4	13.5	-35.2	-
R_x=90 ohms	125	1.8	72.2	40.1	+13.2	16.3
	150	5.4	135.2	25.0	+36.5	-
#831	100	0.5	8.7	17.4	-25.2	-
R_x=125 ohms	125	2.9	24.2	8.4	- 2.8	22.4
	150	3.9	57.8	14.8	+2[illegible].8	-

TABLE IV - CATHODE COUPLED OSCILLATOR PERFORMANCE AT 135 mc.

Crystal	B+ volts	P_x mw	P_e mw	P_e/P_x -	Δf_s ppm	Δf_b ppm
#845	100	0.7	0.8	1.1	-6.3	-
R_x=60 ohms	125	1.5	3.2	2.1	+1.4	-
	150	2.9	6.7	2.3	+5.0	4.7
#846	100	0.9	1.8	2.0	-18.3	-
R_x=100 ohms	125	2.5	3.9	1.5	-11.3	8.2
	150	4.2	8.2	1.9	- 3.1	-

TABLE V - CATHODE COUPLED OSCILLATOR PERFORMANCE AT 150 mc.

B. Grounded Grid Oscillator

The Grounded Grid oscillator circuit is shown in Fig. 14. This circuit is typical of those used for comparative performance determination.

Operational parameters were quite good, with relatively high power ratios and low crystal drive levels. At the higher frequencies, the circuit becomes somewhat more difficult to adjust, although performance is still good.

Tables VI through IX indicate circuit performance obtained from the preliminary tests.

C. Transformer-Coupled Oscillator

The transformer-coupled oscillator, Fig. 15, consists of a grounded cathode amplifier in a tuned-grid tuned-plate arrangement. A pentode having low grid-to-plate capacity is required to prevent oscillation when the crystal is removed from the circuit. Neutralization is required for triode operation. The feedback voltage is obtained from a tap on the plate tank coil and is fed through the crystal to the grid transformer. Either the plate or grid transformer must supply the necessary 180° phase-shift to assure oscillation. If the plate and grid circuits are properly tuned and the leakage inductances of the two transformers are cancelled by tuning C_1 and C_2, operation will be at the series resonant point of the crystal.

The addition of these tuning elements make the transformer-coupled circuit one of the most difficult to adjust. However, when the circuit was constructed and aligned, it was noted that the crystal drive was excessively high and an analysis of the circuit was made to determine if an improvement of operation could be accomplished.

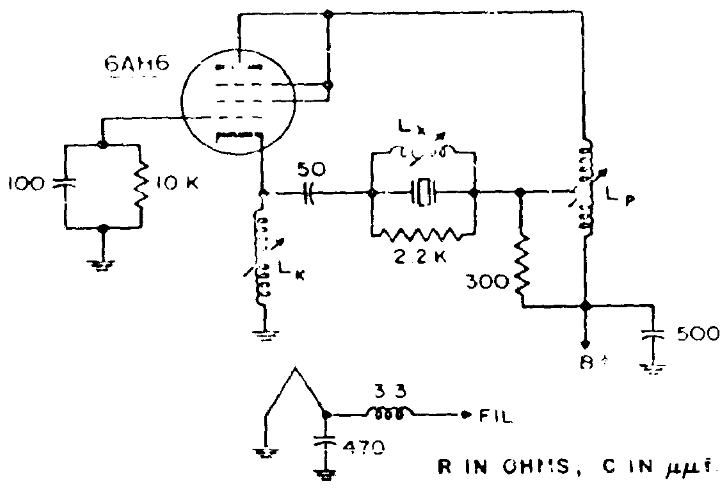


FIG. 14. GROUNDED-GRID OSCILLATOR

Crystal	E_b volts	P_x mw	P_o mw	P_o/P_x -	Δf_s ppm	Δf_b ppm
#703	75	2.8	7.5	2.7	-19.0	-
R_x=22 ohms	100	4.1	16.0	4.0	-11.0	1.4
	125	5.5	33.0	6.0	- 5.0	-
#707	75	0.3	8.0	27.0	- 4.2	-
R_x=707 ohms	100	0.8	13.3	16.6	- 5.9	4.0
	125	2.5	36.3	14.5	+ 3.1	-

TABLE VI - GROUNDED GRID OSCILLATOR PERFORMANCE AT 75 mc.

Crystal	E_b volts	P_x mw	P_o mw	P_o/P_x -	Δf_s ppm	Δf_b ppm
#830	50	0.2	2.1	10.6	-11.1	-
R_x=40 ohms	75	1.4	9.8	6.8	- 2.7	-
	100	4.4	24.2	5.5	+ 7.6	2.8
#828	50	0.2	2.5	15.3	-11.5	-
R_x=60 ohms	75	1.3	9.8	7.4	+ 0.8	-
	100	6.2	24.2	3.9	+13.3	4.2

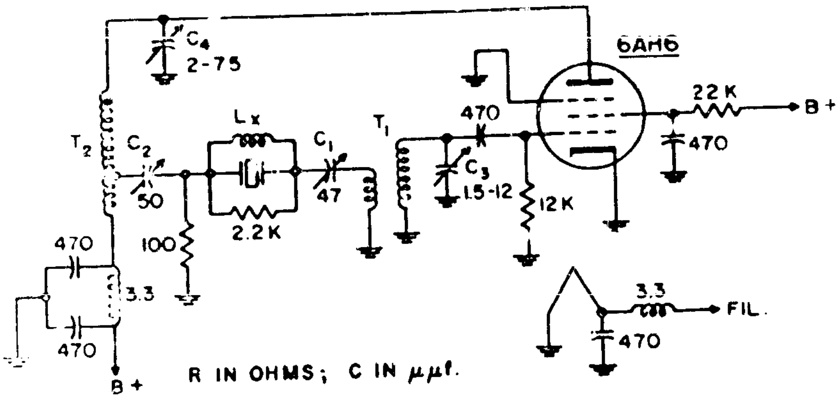
TABLE VII - GROUNDED GRID OSCILLATOR PERFORMANCE AT 105 mc

Crystal	B+ volts	P_x mw	P_o mw	P_o/P_x -	Δf_a ppm	Δf_b ppm
#832	175	1.0	16.2	16.2	-10.5	6.6
R_x=90 ohms	200	2.8	39.2	14.0	- 0.5	-
	225	5.4	72.2	13.3	+ 9.9	-
#831	150	0.7	12.8	18.3	-17.5	-
R_x=125 ohms	175	2.0	28.8	14.4	+ 0.8	7.1
	200	3.9	51.2	13.1	+25.7	-

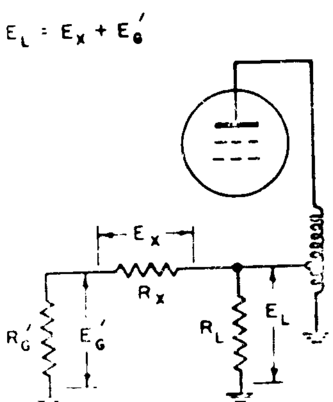
TABLE VIII - GROUNDED GRID OSCILLATOR PERFORMANCE AT 135 mc.

Crystal	B+ volts	P_x mw	P_o mw	P_o/P_x -	Δf_a ppm	Δf_b ppm
#845	60	1.0	2.0	2.0	-18.6	-
R_x=60 ohms	70	4.4	8.7	2.0	-10.5	6.0
	75	6.0	13.0	2.2	- 9.7	-
#847	70	1.4	3.5	2.5	-16.7	-
R_x=90 ohms	75	3.2	8.5	2.7	-11.8	-
	80	5.4	13.4	2.5	-10.0	5.5

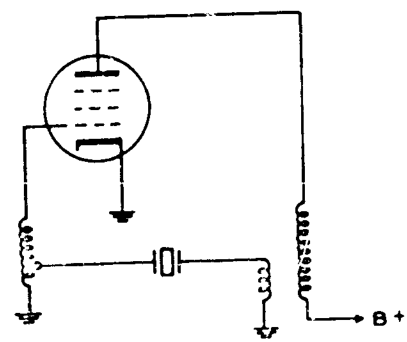
TABLE IX - GROUNDED GRID OSCILLATOR PERFORMANCE AT 150 mc.



A. BASIC OSCILLATOR CIRCUIT



B. EQUIVALENT CIRCUIT OF CRYSTAL FEEDBACK NETWORK



C. ALTERNATE TRANSFORMER ARRANGEMENT OF BASIC CIRCUIT

FIG. 15. TRANSFORMER-COUPLED OSCILLATOR.

Table I shows operation of the circuit at 75 mc.

Reference to Figure 15B shows an equivalent configuration of the basic circuit. The total drive voltage E_L, is distributed across the crystal resistance at resonance, R_x, and the transformed equivalent input resistance of the tube, R_g. This input resistance is a function of the cathode lead inductance, transit time effects, transconductance, and various tube constants. It is well known that as frequency increases, the input resistance of a tube decreases. This input resistance is reflected into the the crystal circuit by means of an autotransformer. Generally, the maximum coupling coefficient for air core inductors is 0.50. Therefore, the reflected resistance is in the order of ten percent of the crystal resistance, causing excessive crystal driving voltage.

For a typical coil used in the circuit at 75 mc, a 4,000 ohm input resistance was transformed to only 6.0 ohms in the crystal circuit. It can be shown, by means of coupled circuit theory, that the reflected resistance is a function of the mutual inductance of the coil. In turn, this inductance is determined by several constants of the coil, which are not readily variable, due to circuit characteristics. Hence, the magnitude of the reflected resistance is fairly fixed, for operations in the desired frequency range.

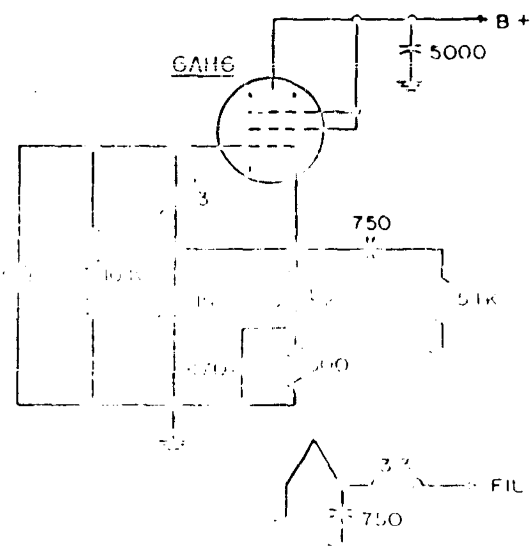
The alternate transformer-coupled circuit of Fig. 15c was tried with similar results. Although power ratios and stability were quite good, the crystal drive levels were prohibitive.

D. Colpitts (Grounded Plate Pierce) Antiresonant Oscillator.

The basic circuit configuration of the Colpitts oscillator is shown in Fig. 16. For overtone operation, the cathode choke coil is

Crystal	B+ volts	P_x mw	P_o mw	P_o/P_x -	Δf_s ppm	Δf_3 ppm
#703	75	2.2	8.2	3.7	-21.0	-
R_x=22 ohms	100	7.3	17.5	3.4	-27.0	3.1
	150	12.8	68.0	5.3	-17.0	-
#707	75	No Oscillations Occurred				
R_x=51 ohms	100	2.5	17.5	7.0	-23.0	3.4
	150	16.0	68.0	4.3	-14.0	-

TABLE X - TRANSFORMER COUPLED OSCILLATOR PERFORMANCE AT 75 mc.



R IN OHMS; C IN μμf.

FIG. 16—COLPITTS ANTIRESONANT OSCILLATOR

selected so that the cathode-to-ground impedance is capacitive only in the range of the desired overtone. For overtones of a lower order, this impedance branch is inductive and the proper phase relations no longer exist. Furthermore, to sustain oscillations under resistive crystal conditions, it is known that the Figure of Merit, M, of the crystal must be at least 2.0 and preferably greater.

Since oscillations could not be obtained at frequencies higher than 60 mc, it was decided to determine what the Figure of Merit was for operation at this frequency. The following parameters were calculated:

f_n = 60 mc (nominal)

f_s = 59992020 cps (series resonant frequency)

f_a = 59995950 cps (parallel resonant frequency using a 10 mmfd load capacitor)

Δf = 3930 cps ($f_a - f_s$)

C_0 = 7.0 mmfd (crystal static capacity)

C_L = 10.0 mmfd (load capacity)

R_e = 30 ohms (effective resistance of the crystal at antiresonance)

C_1 = 0.00223 mmfd (crystal series arm capacity)

L_1 = 3.1 mh (crystal series arm inductance)

From this information it can be calculated that,

Q = 39,000 (series arm Q)

PI = 2340 ohms ($(1/(2\pi f\ C_L))^2 R_e$)

and M = 5.1 (Q/r, where $r = (C_0 + C_L)/C_1$)

To obtain larger values of M would require lowering the value of C_L or lowering the resistance of the crystal. The value of C_L could be lowered by tuning it out with a suitable inductance. However, this transforms the circuit into a Lister configuration, with its attendant disadvantages. Since the resistance of this crystal is already far below the maximum rating specified by MIL-C-3098A, typical crystals would not operate even at this frequency.

E. Bridged "T" Oscillator

The bridged "T" oscillator, when properly adjusted, operates the crystal at approximately series resonance. With the resulting low impedance path through the crystal, this circuit resembles that of the familiar Colpitts. Fig. 17 indicates the circuit configuration used for testing the bridged "T" at 75 and 105 mc. The literature describes operation of the oscillator, with good results, in the VHF frequency range. This was confirmed with good operation at 75 and 105 mc. Stability of this circuit for changes in plate supply were found to be very good at 75 mc, but at 105 mc, the stability is comparable to that of other circuits tested. However, adjustment of the circuit at both frequencies was extremely difficult. It was difficult to adjust the grid drive capacitor and remain within the proper operating range of the resonant elements, consisting of the plate tuning capacitor and the series "T" inductance, since this point was quite critical.

Tables XI and XII below indicate operation at the testing frequencies.

Several methods of improving frequency correlation were tried. One method, noted in the literature, simply consisted of a tuned coil in parallel with the crystal unit. By tuning this coil to a frequency much higher than the series resonant point of the crystal, frequency correlation was improved greatly. However, this brute force method of operation was rejected since, unfortunately, no correlation between the required inductance and the

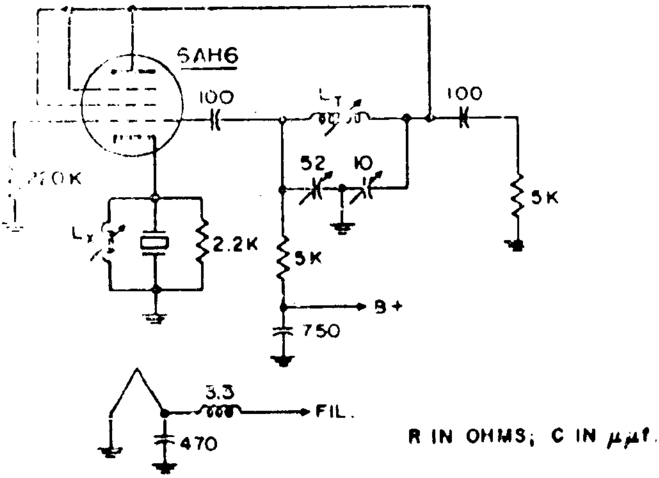


FIG. 17—BRIDGED "T" OSCILLATOR

Crystal	B+ volts	P_x mw	P_e mw	P_e/P_x -	Δf_s ppm	Δf_b ppm
#703	100	1.3	1.6	1.2	-19.5	-
R_x=22 ohms	125	3.8	3.9	1.0	-19.0	-
	150	7.3	7.2	1.0	-16.0	0.7
#707	100	0.1	0.7	7.0	-11.8	-
R_x=51 ohms	125	0.6	2.7	4.5	- 9.1	-
	150	1.2	5.6	4.7	- 8.2	1.7

TABLE XI - BRIDGED "T" OSCILLATOR PERFORMANCE AT 75 mc.

Crystal	B+ volts	P_x mw	P_e mw	P_e/P_x -	Δf_s ppm	Δf_b ppm
#830	75	0.6	1.2	2.0	-12.3	-
R_x=40 ohms	100	2.1	4.8	2.3	-12.7	2.6
	125	4.9	11.0	2.3	-13.1	-
#828	75	0.9	1.4	1.6	-14.3	-
R_x=60 ohms	100	3.2	5.0	1.6	-17.5	2.3
	125	6.0	11.6	1.9	-19.7	-

TABLE XII - BRIDGED "T" OSCILLATOR PERFORMANCE AT 105 mc.

operating frequency could be found. Other methods used to improve Δf_s had undesirable effects on the crystal drive level, since these methods relied on specific changes in the value of the grid drive capacitance.

F. Comparative Circuit Performance

Table XIII lists comparative performance obtained from the four series resonant circuits at 75 and 105 mc. The values listed are averages taken over all crystals and supply voltages used and represent typical obtainable performance. The four circuits tested and evaluated at 75 mc include the Cathode Coupled, Transformer Coupled, Grounded Grid and Bridged "T" oscillators. The Transformer Coupled was not tested at 105 mc, since analysis of the circuit indicated that crystal drive would be prohibitively high.

The difficulty encountered in tuning the Bridged "T" tends to make it less acceptable than the Cathode Coupled and Grounded Grid circuits. Although stability of the Bridged "T" was found to be quite good at 75 mc, both the Cathode Coupled and Grounded Grid circuits yield comparable stabilities at higher frequencies. The Grounded Grid circuit also provides greater output power. On the basis of these results the area of study was narrowed to the Cathode Coupled and Grounded Grid circuits and detailed design information was obtained for these two circuits in the 75 to 150 mc frequency range. Comparative performance at 135 and 150 mc is shown on Table XIV.

Performance of the two circuits is comparable to that obtained at lower frequencies. Good power ratios were obtained with nominal levels of crystal drive. Frequency stability is somewhat poorer due both to lower quality crystals and more critical circuit adjustment. However, this change is only a few parts per million for a ten percent change in supply voltage.

Frequency mc	Circuit type	P_x mw	P_o mw	P_o/P_x -	Δf_s ppm	Δf_b ppm
75	Cathode Coupled	4.0	16.0	4.0	9	2.0
	Transformer Coupled	8.0	40.0	5.0	10	3.0
	Grounded Grid	4.0	50.0	12.5	8	3.5
	Bridged "T"	3.0	7.0	2.3	9	1.0
105	Cathode Coupled	2.5	11.0	4.4	3	3.0
	Grounded Grid	5.0	30.0	6.0	9	3.5
	Bridged "T"	3.0	6.0	2.0	14	3.0

TABLE XIII - COMPARATIVE CIRCUIT PERFORMANCE AT 75 and 105 mc.

Frequency mc	Circuit type	P_x mw	P_o mw	P_o/P_x -	Δf_s ppm	Δf_b ppm
135	Cathode Coupled	2.0	13.0	6.5	9	5
	Grounded Grid	2.5	25.0	10.0	8	7
150	Cathode Coupled	2.0	12.0	6.0	10	5
	Grounded Grid	2.5	20.0	8.0	12	6

TABLE XIV - COMPARATIVE CIRCUIT PERFORMANCE AT 135 and 150 mc.

On the basis of the performance information presented above, the Cathode Coupled and Grounded Grid circuits were selected for development of detailed design data for general application. This development and design method are discussed in later sections of this report. However, other circuit arrangements have particular advantages for certain special applications. For example, when filament-type tubes are used it is convenient to use a grounded cathode circuit configuration. Circuits investigated specifically for use with filament tubes were the Grounded Grid, the Feedback or Heegner, the Bridged "T" and the Capacitance Transformer Coupled circuit; the latter circuit was conceived during the course of this program for this specific application.

Completely satisfactory results were obtained only with the Capacitance Transformer Coupled circuit. Some information was obtained on the Grounded Grid circuit utilizing a 5971 subminiature triode but the circuit operates as a crystal stabilized oscillator rather than a true crystal controlled circuit. As a result the circuit is not as stable as may be desired and is prone to uncontrolled oscillations. However, this data along with complete performance information on the CTC circuit is contained in Section IV of this report. Nothing close to satisfactory operation was obtained with the Feedback or Bridged "T" circuits with the low transconductance tubes available.

G. <u>Circuit and Component Characteristics and Measuring Techniques</u>

During the course of these preliminary measurements certain constructional and component characteristics common to all circuits were determined and are discussed in the following paragraphs.

The difficulties encountered in designing circuits to operate above 100 mc center around two main considerations: circuit layout and component characteristics. In the frequency range of interest, the usual care in layout of the circuit may be adequate; however, several problems encountered will be discussed here. Proper grounding of elements is difficult to obtain. At these frequencies, the lengths of leads connecting various grounded components have considerable inductive reactance. It was found that if the center post of the tube socket was the primary grounding source, with minimum lead lengths to other points, measurement problems and spurious circuit responses were minimized. Filament decoupling networks were wired directly at the socket to eliminate undesirable cathode pickup. This was also done for the plate networks. Because of lead inductance, the use of the grid-dip oscillator method of aligning coils is made more difficult. Extraneous responses sometimes overshadow the true coil resonant point; however, proper by-passing eliminates this trouble. It was also found that in order to check a coil in the circuit, it was sometimes necessary to short out any other tuned inductance in the oscillator loop which might produce an erroneous response.

It is well known that component impedance characteristics in the frequency range of interest differ from their characteristics at lower frequencies. Resistors of high ohmic value are generally slightly capacitive; however, the resistance values vary considerably with frequency. For 5000 ohm half-watt composition resistors, the actual measured values ranged from 20 percent to 30 percent lower. At twice this value, errors produced were as high as 50 percent or more. Capacitors tend to become inductive due to lead length, this effect being more severe for higher capacitance values. Small values of capacitance, of about 100 mmfd or less, exhibited good reactance characteristics. Small silver mica capacitors show very little loss, but disc and tubular ceramic capacitors show parallel loss resistances as low as a few hundred ohms.

Crystal units used in the program were, in general, obtained from either USASEL or commercial manufacturers. All the types used were wire mounted units, placed in HC-6/U or HC-18/U holders. Specifications for crystals operating above 87 mc are not available. However, for the desired frequency range, fifth or seventh overtone units were used, assuming a maximum series resonant resistance of 60 ohms up to 125 mc and 100 ohms to 150 mc. Generally, commercial units having these specifications were obtainable. Unfortunately, few manufacturers have had success in producing reliable units. Common problems included crystal fracture and excessive series resonant resistance. Very few units exhibited spurious modes.

Crystal parameters were measured in the TS-683/TSM Crystal Impedance Meter. However, for measurement of high frequency units, the AN/TSM-15[7,8] was made available to the program. This meter is capable of testing crystals in the 75 to 200 mc frequency range.

The power dissipation of a crystal as normally measured is a function of both crystal resistance and the voltage across it. Accuracy of power determination is then dependent on the accuracy of crystal impedance and voltage measurements. The accepted method of determining crystal resistance [illegible] measurement in a crystal imp[illegible]ce meter such as the TS-683/TSM. When a substitution resistor, having the same value as the resistance of the crystal, is placed in the CI meter circuit, the frequency of operation and the grid current will remain the same as that obtained with the crystal. This method yields a measurement of crystal network resistance at the operating frequency with an accuracy of a few percent. Substantial errors in the measured value of crystal drive level may be introduced by voltmeter inaccuracies and non-sinusoidal crystal voltage waveforms. Even an exact rms value of crystal voltage does not necessarily result in an accurate power determination since the crystal network offers different values of impedance to the harmonics present in the feedback circuit and contained in the voltage waveform across the crystal network. Using the rms voltage reading and the measured crystal resistance to compute drive level results in an indicated drive higher than the true value with non-sinusoidal waveforms.

During the comparative performance investigation of the different crystal oscillators an effort was made to decrease the errors in drive level determination due to crystal voltage measurement difficulties. Drive level measurement reported previously had been determined by measurement of the voltage between each side of the crystal and ground and taking their difference. Diode detector circuits were built into each experimental circuit to provide the individual readings. It was found that considerable error in difference voltage measurements is caused by dissimilarities in the characteristics of the diodes. This caused difficulty in actual measurement as well as in comparison of performance of all the circuits since each contained a different pair of diodes. In order to improve the accuracy of measurement and comparison of circuit performance several voltage measuring techniques have been investigated and one method was chosen which resulted in a probe design yielding greatly improved crystal voltage measurements.

The first method tried consisted of a dual crystal probe used in conjunction with a modified vacuum tube voltmeter (VTVM). The circuit of the dual probe is identical to that of the test oscillators except that a pair of 1N90 diodes are used because of their small size in comparison to that of the 1N34. The VTVM is modified by adding an attenuator in the grid that is normally returned to ground through a contact bias network. This attenuator circuit, which is wired onto the range switch section in place of the ohmmeter range resistors, is similar to the normal attenuator, except that it has a potentiometer in the ground end. This is adjusted for zero indication, when both diodes are receiving the same signal voltage, which changes the sensitivity of one metering section to compensate for dissimilar diode characteristics. The modified portion of the VTVM is shown schematically in Fig. 18. This system results in considerable improvement over the use of individual voltage readings when the probe circuit is wired into the test chassis, but it is difficult to maintain balance when built into the form of a probe. The voltage indication is not only a function of voltage difference but also of the level of voltage into each side of the measuring system. Since one of the prime purposes of a redesigned crystal voltage indicator is for comparison of crystal drive in different circuits a wired-in probe circuit is not practical.

To eliminate the problem of balance being a function of signal level a differential probe was constructed having the circuit shown in Fig. 19. This circuit utilizes two diodes connected to provide the difference voltage at the output of the probe. A balance potentiometer is connected at the voltage readout point which in turn is connected to a standard VTVM. When

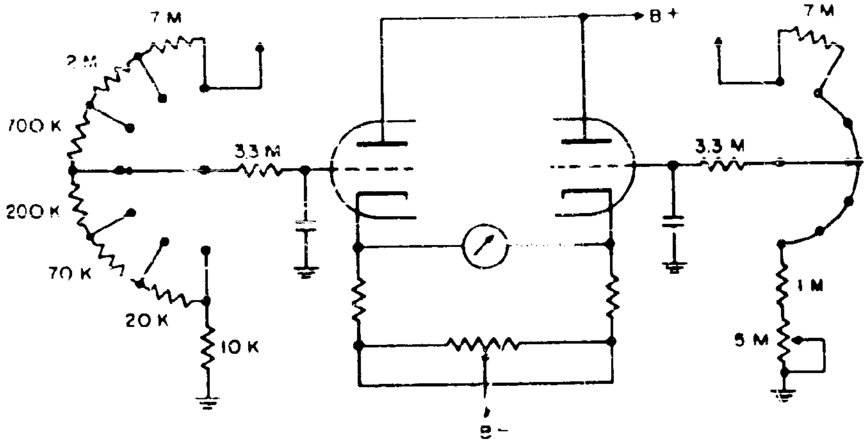


FIG. 18—MODIFIED VTVM CIRCUIT

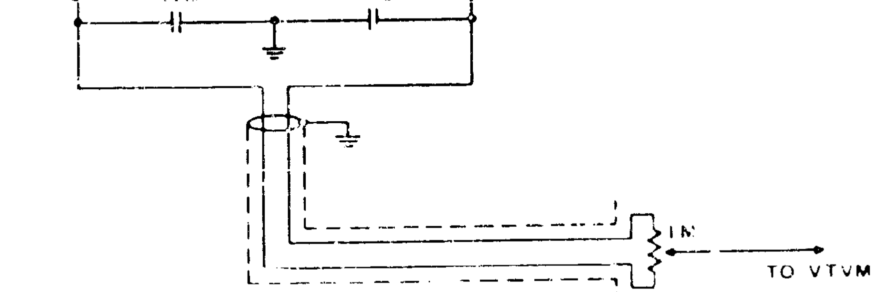


FIG. 19 EXPERIMENTAL DIFFERENTIAL PROBE.

properly balanced and using an infinite impedance meter, the output voltage is one-half of the true difference voltage. However, this varies in practice with input level because of dissimilar diode characteristics. By using a matched pair of diodes (1N35) the variation with input level is decreased but a calibration curve as a function of input level for each pair of diodes is necessary to obtain reasonable accuracy.

Since a direct indication of difference voltage is preferrable, a 1N35 matched diode pair was used with the modified VTVM. This proved satisfactory but could not be built into the desired probe arrangement because of size requirements. To alleviate this problem a matched pair of Hughes 1N67A's (MP-3002A) were wired into the test chassis and performed satisfactorily. However, when these were installed in the compact probe arrangement the indicated difference voltage again appeared to be a function of signal input level, though not to the extent experienced with the 1N34 diodes used in the first probe design. Further investigation showed this effect to be due to improper shorting of the two probe inputs for zero adjustments.

It was found that the use of similar shorting methods for both the probe and the diode test circuit provided improved results. Additional tests showed that some of the remaining difficulty was due to nonlinearity of the vacuum tube circuits in the VTVM. This is reduced to acceptable limits by the meter balancing technique. Balancing and zero adjustment can best be explained by reference to the complete probe circuit which is shown in Fig. 20. To balance the meter and read true differential voltage the probe is first plugged into the crystal socket of a circuit under test. The probe is then shorted by plugging a crystal base, having a good radio frequency short across it, into the probe. The switch in the probe metering circuit is then turned so that it grounds the modified side of the VTVM circuit. This voltage reading is then noted and the normal input of the VTVM is grounded. The VTVM polarity switch is then set to the opposite polarity, and the potentiometer in the modified attenuator circuit is adjusted to give the same meter indication. With the meter probe switch returned to its center position the meter adjustment is complete. Comparison readings with calibrated laboratory voltmeters show this voltage indication to be accurate within five to ten percent for all values of drive over a few tenths of a milliwatt for typical crystals. For drive levels in the order of 0.1 milliwatt the voltage accuracy is approximately 20 percent.

Although this accuracy is not all that could be desired it is a great improvement over the previously used technique, especially for comparison of drive level between different circuits since the same measuring system is used in all cases. It also represents improvement over the use of a single meter and probe to take two readings since circuit operation is not changed by moving a probe from one side of the crystal to the other.

The balanced rectifier probe has been built into an HC-13 crystal holder. A crystal socket is mounted as a part of the probe assembly. The probe can be plugged into an oscillator crystal socket and the crystal plugged into the probe socket. The probe is left in place for all testing and performance measurements and is removed when satisfactory operation has been obtained and the circuit is put into use in an equipment. Differential voltmeters have been designed for use at lower frequencies but the input capacitance of the probes was too great for use at high frequencies. This probe configuration, and the low shunt capacitance of the diodes used,

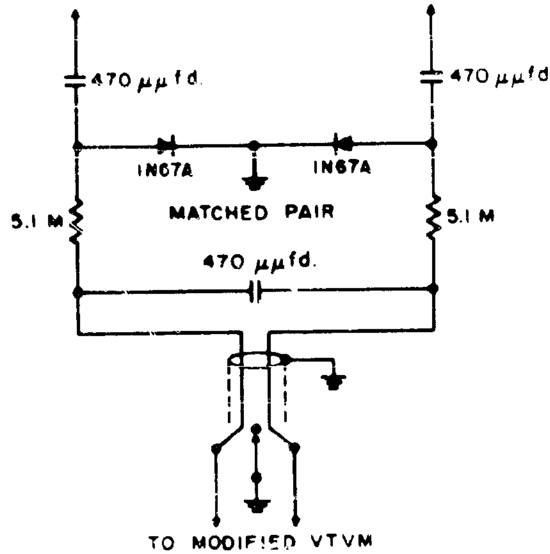


FIG. 20—BALANCED PROBE SCHEMATIC

FIG 21—DETAILS OF THE BALANCED PROBE

results in an input capacity of approximately 2.0 mmfd.

Photographs of the final probe design showing internal constructional details and the complete enclosed probe are show in Fig. 21. The photograph on the left shows the position of all components. The two input coupling capacitors are standard disc ceramic units with their insulating coating removed and connections made directly to the plating. On the right is shown the completed probe with a crystal unit in place.

Fig. 22 shows a typical laboratory setup used in determining crystal oscillator performance. The balanced probe with the crystal in place is plugged into the test chassis crystal socket. The output and crystal voltmeters are in the background. The output meter is the Hewlett-Packard 410B, and has its probe plugged into a tip jack on the oscillator chassis. Directly below this probe is the connecting line to a frequency counter. The crystal difference voltmeter was constructed from a kit with proper modification to allow differential voltage indication. The probe switch, which allows reading of either differential voltage or the voltage from either side of the crystal to ground, is visible in front of the lower center of the meter panel. The test assembly shown is typical of that used for determining and verifying the design information contained in Appendix I of this report.

FIG. 22 — LABORATORY SETUP FOR CRYSTAL OSCILLATOR PERFORMANCE MEASUREMENTS.

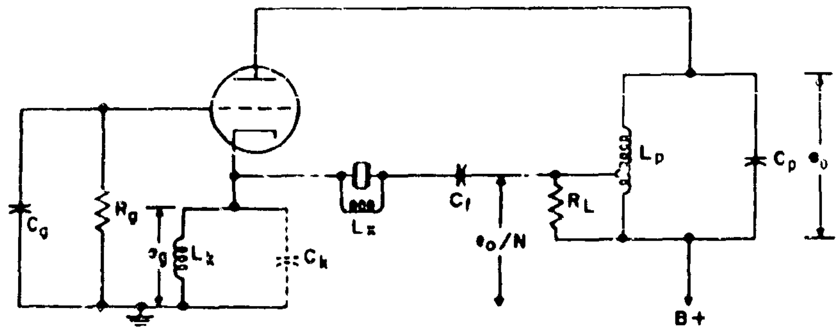
III. ANALYSIS OF CIRCUIT OPERATING CHARACTERISTICS

In order to compare the experimental results of the circuits under consideration with theoretical expectations, it is necessary to develop and analyze the loop gain equations for these circuits. The equations derived below contain certain simplifying assumptions. These result in easily understood relations which prove useful for comparing qualitative results, but provide very little quantitative information. However, the use of these equations in conjunction with measured performance data results in a useful relationship for the design of series resonant crystal oscillator circuits and prediction of their performance.

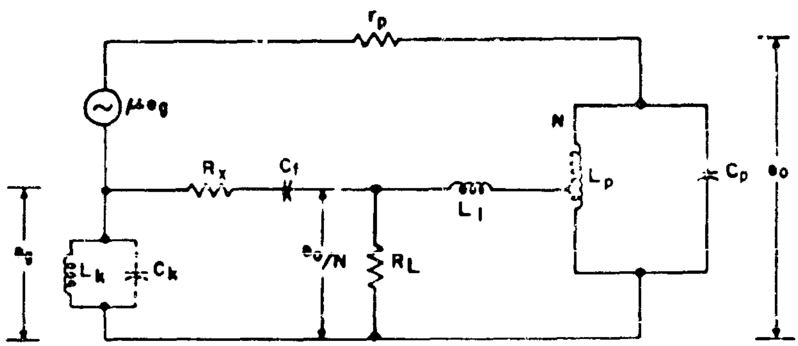
Six circuits are analyzed. These are the Grounded Grid, Cathode Coupled, Transformer Coupled, Bridged "T", Feedback, and Capacitance Transformer Coupled oscillators. Although only the first two and the last circuits are utilized in later developments, the others are of interest and their equations are presented and discussed here. The next section, which deals with the experimental determination of circuit performance will be concerned only with the Grounded Grid and Cathode Coupled circuits for general applications and the Grounded Grid and Capacitance Transformer Coupled oscillators for special applications.

A. Analysis of the Grounded Grid Oscillator

The Grounded Grid oscillator circuit is shown in Fig. 23. The feedback voltage is obtained from a tapped plate coil and is applied through the crystal network to the input of the Grounded Grid Triode amplifier stage. For the crystal to operate at exactly series resonance, there must be zero phase shift throughout the loop circuit. As a result, the phase shifts produced by individual circuit stray reactances must be compensated by circuit



(A) CIRCUIT SCHEMATIC



(B) EQUIVALENT CIRCUIT

FIG 23 – GROUNDED GRID CRYSTAL OSCILLATOR design, or crystal operation will be at other than the series resonant frequency of the crystal network as measured in a crystal impedance meter. The input (cathode-to-ground) capacitance of the tube is tuned with the cathode coil, L_k, at the operating frequency. The load and plate circuit capacitances are tuned with the plate coil, L_p. The leakage inductance of the plate coil, which effectively appears at the tap point, is tuned with C_f, although this is not a critical element. Under these conditions, when the plate coil is tuned to resonance, oscillations will occur at the series resonant frequency of the crystal.

The equivalent circuit of Fig. 23B shows the more important stray reactances. For this circuit the loop gain is given by:

$$G = A_{gg} A_x / N \qquad (1)$$

where A_{gg} is the voltage gain of the grounded grid amplifier, N is the ratio of the oscillator plate voltage to the tap voltage, and A_x is the ratio of the grounded grid input voltage to the tap voltage. All loading effects are included in R_L which is shown from the tap to ground. The individual gains are given by the following expressions:

$$A_{gg} = \frac{g_m N^2 R_L \left(R_x + \frac{1}{g_m}\right)}{R_L + R_x + \frac{1}{g_m}} \qquad (2)$$

$$A_x = \frac{\frac{1}{g_m}}{R_x + \frac{1}{g_m}} \qquad (3)$$

where R_x is the series resonant crystal resistance, g_m is the tube transconductance, and the effective amplifier load (for gain purposes) is the transformed impedance of R_L in parallel with the impedance looking into the crystal network from the transformer side. It is assumed that the effective plate load is small compared to the plate resistance of the tube. The loop gain, G, is then given by:

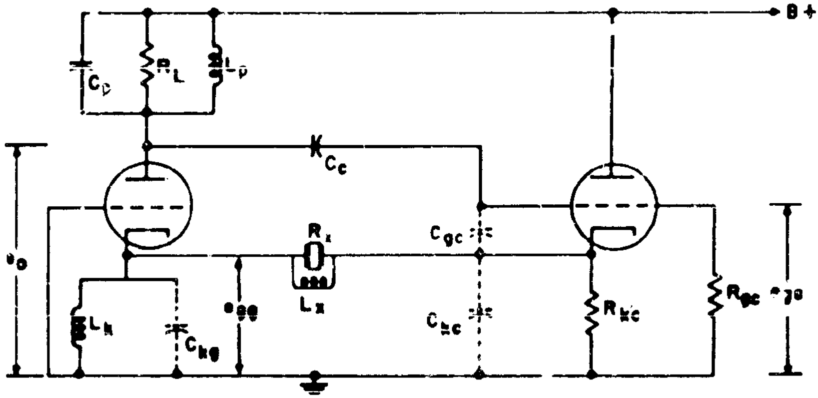
$$G = \frac{NR_L}{R_L + R_x + \frac{1}{g_m}} \quad (4)$$

The loop gain must be greater than unity for oscillations to start. Once started, the transconductance of one or both tubes decreases until the right hand expression of equation (4) is equal to unity and equilibrium conditions exist. Since the amplitude of steady state oscillation is proportional to the initial value of loop gain, it can be seen that the amplitude of oscillation will increase for increasing values of N and g_m and decrease for increasing crystal resistance, R_x. The effect of R_L is not linear, but, in general, increasing values of R_L will result in increased amplitude of oscillations.

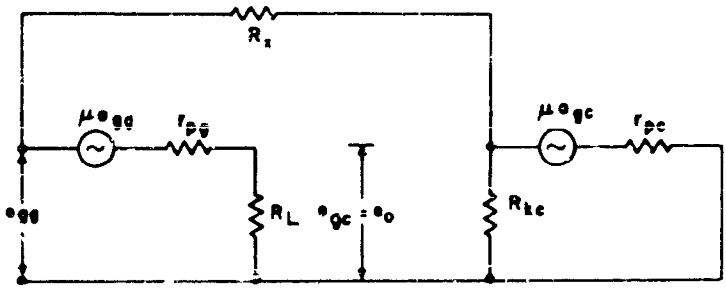
Frequency stability considerations and certain performance characteristics peculiar to operation of the Grounded Grid oscillator at low frequencies (10 - 40 mc) are discussed in the final paragraphs of the section devoted to the analysis of the Cathode Coupled oscillator which follows.

B. Analysis of the Cathode Coupled Oscillator

The cathode coupled crystal oscillator circuit is shown in Fig. 24. Two triodes are used, one as a grounded grid amplifier, the other as a cathode follower. Feedback is supplied through the low impedance path of the crystal at series resonance between the two cathodes. Since there must be zero phase shift around the circuit loop, phase shifts caused by the various stray reactances must be compensated by circuit design. The cathode follower can



(A) CIRCUIT SCHEMATIC



(B) EQUIVALENT CIRCUIT

FIG. 24 — CATHODE COUPLED CRYSTAL OSCILLATOR

be made substantially free of phase shift over a wide frequency range by making $C_{gc}/g_{mc} = C_{kc}R_{Lk}$, where g_{mc} is the transconductance of the cathode follower tube and R_{Lk} is its total load resistance. The amplifier input capacity, C_{kg}, can be antiresonated with L_k at the operating frequency. A representation of the equivalent circuit is shown in Fig. 24B. In this circuit, it is assumed that L_p tunes C_p, L_k tunes C_{kg}, $C_{gc}/g_{mc} = C_{kc}R_{Lk}$, L_x tunes the crystal static capacity, C_c has negligible reactance at the operating frequency, and that R_L includes the useful load as well as the input resistance offered by the cathode follower circuit. It is also assumed that R_{kc} is large compared to the crystal resistance and the grounded grid amplifier input impedance. Under these conditions, the cathode follower load resistance is merely the crystal resistance, R_x, in series with $1/g_{mg}$, the amplifier input impedance. Therefore, when the plate tank is tuned to resonance, oscillations will occur at the series resonant frequency of the crystal.

The conditions necessary for oscillation in the cathode coupled crystal oscillator can be determined from the loop gain of the circuit. The loop gain, G, is given by:

$$G = A_{gg}A_{cf}A_x \tag{5}$$

where A_{gg} is the voltage gain of the grounded grid amplifier, A_{cf} is the voltage gain of the cathode follower, and A_x is the ratio of the grounded grid amplifier input voltage to the cathode follower output voltage. The individual gains are given approximately by the following expressions:

$$A_{gg} = g_{mg}R_L \tag{6}$$

$$A_{of} = \frac{g_{mc}(R_x + \frac{1}{g_{mg}})}{1 + g_{mc}(R_x + \frac{1}{g_{mg}})} \qquad (7)$$

$$A_x = \frac{\frac{1}{g_{mg}}}{R_x + \frac{1}{g_{mg}}} \qquad (8)$$

Then,

$$G = \frac{R_L}{R_x + \frac{1}{g_{mg}} + \frac{1}{g_{mc}}} \qquad (9)$$

The loop gain, G, must be greater than unity for oscillations to start. The initial value of equation (9) is proportional to the equilibrium amplitude of oscillation, and it can be seen that the amplitude of oscillation increases for increasing values of R_L and g_m and decreases for increasing crystal resistance, R_x.

Circuit evaluation and performance measurements on the Cathode Coupled and Grounded Grid circuits in the range of 10 to 75 mc revealed problems of frequency and crystal voltage correlation. It has been determined that for the same tuning procedure used at higher frequencies, the operating frequency is above f_s by 20 to 25 parts per million, in the range of 10 to 40 mc. At higher frequencies this correlation problem becomes negligible. Investigations in this frequency range have shown the problem to be common to both circuits. Tuning for maximum output caused the crystal to operate inductive ($f_o > f_s$) and it was determined experimentally that placing an inductance reactance equivalent to that of the crystal, at the original operating frequency, in series with the crystal and retuning for maximum output provided operation at or near f_s. It was decided to use some form of compensation since operation at f_s is highly desirable.

In an effort to determine the reason for the frequency effects discussed above a further analysis of the circuits was made. It had been assumed in preliminary analysis that tuning the cathode and plate circuits and the leakage inductance of the Grounded Grid plate coil should provide resistive operation of the crystal. Since inductive operation is common to both circuits the leakage inductance would not be the cause. The condition of the plate tank after tuning to maximum output was investigated and it was determined that it could not have caused the amount of phase shift being encountered. The tuning condition of the cathode circuit was also shown to be unable to cause this effect, since it could not compensate unless it were detuned considerably to the capacitive side of resonance. Study of the various stray reactances shows only one that has not been considered in a loop phase analysis of either circuit. This is the reactance of the plate-to-cathode capacity. The coupling circuit from plate to cathode was analyzed to determine if the presence of this capacitance would tend to produce the measured effects. A general network, shown in Fig. 25, was considered. An ideal transformer having a turns ratio and voltage ratio of 1:n is assumed, R is the resistive input impedance of the grounded grid amplifier, Z_x is the operating crystal series impedance, and C_{pk} is the direct plate to cathode capacitance.

The circuit admittance parameters defined by:

$$I_1 = Y_{11} E_1 + Y_{12} E_2 \tag{10}$$

$$I_2 = Y_{21} E_1 + Y_{22} E_2 \tag{11}$$

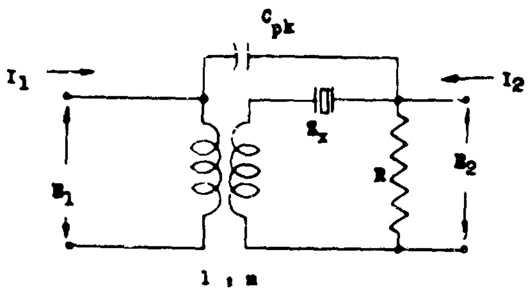


Fig. 25 - Idealized Plate-To-Cathode Coupling Network.

are,

$$I_1 = \left[\frac{n^2}{Z_x} + j\omega C_{pk}\right] E_1 - \left[\frac{n}{Z_x} + j\omega C_{pk}\right] E_2 \tag{12}$$

$$I_2 = -\left[\frac{n}{Z_x} + j\omega C_{pk}\right] E_1 + \left[\frac{Z_x + R}{Z_x R} + j\omega C_{pk}\right] E_2 \tag{13}$$

Since the output current I_2 is zero, the ratio

$$\frac{E_2}{E_1} = -\frac{Y_{21}}{Y_{22}} = \frac{nR + j\omega C_{pk} Z_x R}{R + Z_x + j(\omega C_{pk} Z_x R)} \tag{14}$$

Rationalization and equating of the imaginary part to zero shows that there will be no phase difference between E_1 and E_2 when Z_x has a reactive part (X_x) given by

$$X_x = \frac{n}{2\omega C_{pk}} \pm \sqrt{\frac{n^2}{4\omega^2 C_{pk}^2} - R_x(R + R_x - nR)} \tag{15}$$

Selection of the negative sign for the value of the radical provides the largest value for the ratio E_2/E_1 and thus is the proper solution. A crystal of zero resistance requires no series reactance for the coupling circuit assumed here since the ideal transformer always has the 1:n voltage ratio. The developed equation of reactance does not readily simplify to show the circuit requirements. It does show, however, that a specific relationship must exist between C_{pk} and the positive reactance in the series feedback path.

The result points out two possibilities for improving frequency correlation. One is to provide an inductor in series with the crystal. The other is to change C_{pk} to bring the correlation figure within acceptable limits. A factor which helps to reduce the effect at higher frequencies is that considerable reactance is present in the series leads to the crystal. Reduced values of C_{pk} cannot be obtained for experimental evaluation; however, increasing C_{pk} corrects the frequency but greatly decreases the output. To achieve complete correlation at 10 mc, for example, it was necessary to add 30 mmfd to the tube and wiring capacity already present which lowered the output to that obtained at 150 mc for similar circuit operating conditions. The use of a series inductor provides frequency correction regardless of the crystal terminal to which it is connected, but to provide good correlation of crystal voltage as well, it must be placed between crystal and input of the grounded grid stage. Crystal voltage correlation is considered as having been obtained when equal voltages are measured across the crystal or a resistor equal to the crystal resistance. This requires that the crystal operate resistively.

The above development does not yield design results of sufficient accuracy since it indicates series inductance values considerably smaller than have been determined experimentally. It does, however, demonstrate that the presence of C_{pk} contributes to the positive reactance operation of the crystal, which, as was discussed previously, is less severe at higher frequencies.

The frequency stability factors of series resonant crystal oscillators has been developed by Edson[2], and are defined in terms of the loop phase shift. To compare various crystal driving methods, a reference phase angle, λ, is defined as that of the self-impedance of the series arm of the equivalent crystal impedance, consisting of L_1, C_1 and R_1. It can then be shown that the stability factor, S_r, used as the reference, is given by:

$$S_r = \frac{2Q}{1 + \tan^2\lambda} \tag{16}$$

where

$$Q = \frac{\omega L_1}{R_1} = \frac{1}{\omega C_1 R_1} \tag{17}$$

and

$$\omega = \omega_o = \frac{1}{\sqrt{L_1 C_1}} \tag{18}$$

for relatively high values of Q.

S_r will be a maximum when $\tan\lambda = 0$. For other values of the angle, the stability factor will be degraded by an amount defined as the degradation factor, given by

$$D_o = 1 + \tan^2\lambda \tag{19}$$

This degrading factor holds for crystals that have no shunt capacitance or coupling to spurious, parasitic resonances when operating at the desired mode. For circuit conditions that provide additional degradation of the stability factor, equation (16) becomes

$$S_f = \frac{2DQ}{1 + \tan^2\lambda} \tag{20}$$

For the circuits under consideration here, the crystal is, in general driven between two resistive elements, R_a and R_b. If a compensating coil is used to cancel the effects of the crystal shunt capacitance, C_o, and a minimum transmission loss is assumed, the Q degradation may be calculated.

It can be shown that, if the sum of R_a and R_b is held constant, such that

$$R_t = R_a + R_b \tag{21}$$

then, for a fixed Q degradation, R_a must be equal to R_b. For this condition, then, where $R' = R_a = R_b$,

$$D = \frac{R_1}{(R_1 + 2R')} \tag{22}$$

and

$$S_f = \frac{2R_1Q}{(1 + \tan^2\lambda)\ (R_1 + 2R')} \tag{23}$$

It is apparent from equation (23), that if R' is made small, the degradation is reduced. However, this is increased at the expense of transmission loss. Nevertheless, for the circuits described in this report, the crystal is generally driven between relatively high resistances. The values of R_a and R_b are usually in the order of several hundreds of ohms. Although crystal Q is degraded considerably, the drive level is kept within reasonable limits and stability is still good.

C. Analysis of the Transformer Coupled Oscillator

The Transformer Coupled oscillator circuit is shown in Fig. 26. A single grounded cathode pentode amplifier stage is used in a tuned-plate tuned-grid arrangement. The feedback voltage is obtained from a tap on the plate coil, L_p, and is applied, through the crystal network, to the grid transformer, L_g. Loop phase shift is zero when the various stray reactances are compensated. The load and stray plate capacitances are tuned with L_p. The leakage inductance of L_p is tuned with C_f. The grid circuit capacitance is tuned by the secondary of L_g. The static capacitance of the crystal, C_o, is cancelled by L_x. Under these conditions, when the plate coil is tuned to resonance, oscillations will occur at the series resonant frequency of the crystal.

The equivalent circuit is shown in Fig. 26B. Here, it is assumed that all stray reactances are tuned and are represented in the circuit as resistances. For this circuit, therefore, the loop gain equation is given by:

$$G = A_{gc} A_x N_g / N_p \tag{24}$$

where A_{gc} is the voltage gain of the grounded cathode amplifier, A_x is the ratio of the grid coil primary voltage to the plate coil tap voltage, N_p is the ratio of the oscillator plate voltage to the tap voltage and N_g is the ratio of the grid coil primary-to-secondary voltage. All loading effects are included in R_L, which is connected from the plate coil tap to ground. The individual gains are then given by the following expressions:

$$A_{gc} = \frac{g_m N_p^2 R_L (R_x + r_g/N_g^2)}{R_L + R_x + r_g/N_g^2} \tag{25}$$

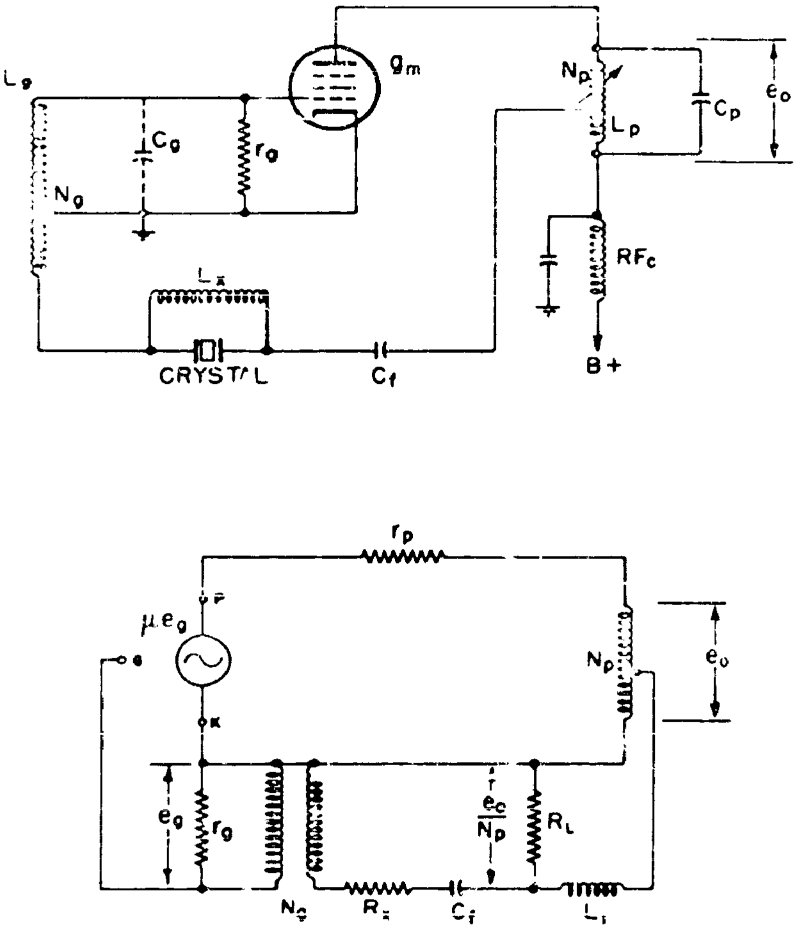


FIG. 26 - TRANSFORMER COUPLED CRYSTAL OSCILLATOR

$$A_x = \frac{r_g/N_g^2}{R_x + r_g/N_g^2} \qquad (26)$$

where g_m is the transconductance of the tube, R_x is the series resonant crystal resistance, and r_g is the total grid circuit load. The loop gain, G, is then

$$G = \frac{g_m N_p N_g R_L r_g}{N_g^2(R_L + R_x) + r_g} \qquad (27)$$

Oscillation will start when G is greater than unity. The amplitude of oscillation will increase for increasing values of all the circuit parameters in the numerator of equation (27), and will decrease for increasing values of crystal resistance.

A discussion of frequency stability considerations, which are common to all series resonant circuits, is given in the section on the Cathode Coupled oscillator.

Further experimental investigation of this circuit was not warranted in view of the results outlined in Section II. In general, the circuit exhibits an excessive crystal drive. This is due to the physical properties of the grid circuit transformer. The grid impedance reflected into the crystal circuit is too low when typical coils are used. This condition becomes worse at the higher frequencies due to the small coil coupling coefficients obtainable. In addition, circuit tuning is quite difficult because of the large number of tuning adjustments.

D. Analysis of the Bridged "T" Oscillator

Two forms of the equivalent circuit of the Bridged "T" oscillator are shown in Fig. 27. The output of the triode amplifier stage is developed

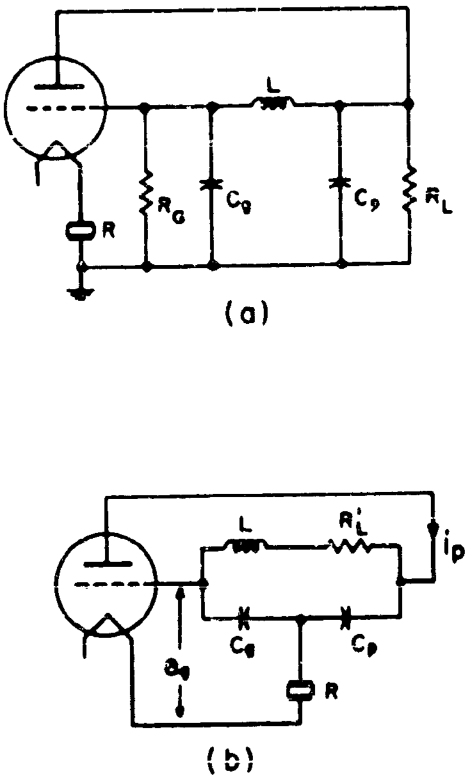


FIG. 27—BRIDGED "T" OSCILLATOR.

across the load in the plate circuit. The feedback network consists of a bridged "T" network, where the cross arm elements are composed of the tuning coil, L, in parallel with the series combination of the capacitors C_p and C_g. The crystal comprises the vertical arm impedance. C_p and C_g are combinations of physical and stray capacitances in the plate and grid circuits, respectively. By compensating the shunt capacitance of the crystal with the coil, L_x, and tuning L, with C_p and C_g to resonance, the loop circuit will be substantially free of phase shift and oscillation will occur.

Fig. 27a shows the equivalent circuit of the Bridged "T" oscillator, where r_g is the impedance of the grid circuit, R_L includes all plate circuit losses, R_x is the series resonant resistance of the crystal, and C_p, C_g, and L are defined above. If the grid and plate circuit losses are combined into a single equivalent series loss, R_L', which also includes the coil loss, then the equivalent circuit assumes the form shown in Fig. 27b.

If L, C_p, and C_g are tuned to the series resonant frequency of the crystal, the transfer impedance of the bridged "T" network, defined by the ratio of the output voltage to the input current, is given by:

$$Z_t = R_x - \frac{X_{C_p} \; X_{C_g}}{R_L'} \tag{28}$$

On the basis of the constant current generator equivalent circuit of the tube, the input current is

$$i_p = - g_m e_g \tag{29}$$

and

$$Z_t = -1/g_m \tag{30}$$

This is the condition for steady-state oscillation. The loop gain equation is

$$G = - g_m Z_t = g_m \left(\frac{X_{C_p} X_{C_g}}{R'_L} - R_x \right) \tag{31}$$

Loop gain tends to increase with increases in the tube transconductance and will decrease with increases in C_p, C_g, R'_L, and R_x. Since r_g and R_L both become smaller at the higher frequencies, indicating and increase in R'_L, it is expected that operation of this circuit at higher frequencies may become marginal. This has been verified experimentally.

The circuit has not been investigated in great detail, since preliminary performance measurements indicate a lack of desirable operating characteristics. When used with subminiature filament-type tubes and typical circuit parameter values, a loop gain of approximately unity is obtained, which is marginal from the standpoint of both starting and operating characteristics.

E. Analysis of the Feedback Oscillator

The circuit diagram of the Feedback oscillator is shown in Fig. 28. Although operation is indicated with the use of subminiature filament type triode tubes, the analysis presented is applicable to other types as well. The circuit, with the crystal removed, is basically a tuned-plate tune-grid configuration. The output is developed across the plate coil, L_{p2}, of the second triode. The feedback voltage is obtained from a tap on this coil and is fed back through the crystal network to the grid circuit of the first triode. The output voltage of this tube is developed across its plate coil, L_{p1}, and is applied to the grid of the second tube. The combination of L_{p2} and the plate and load capacitances are tuned to the resonant frequency of

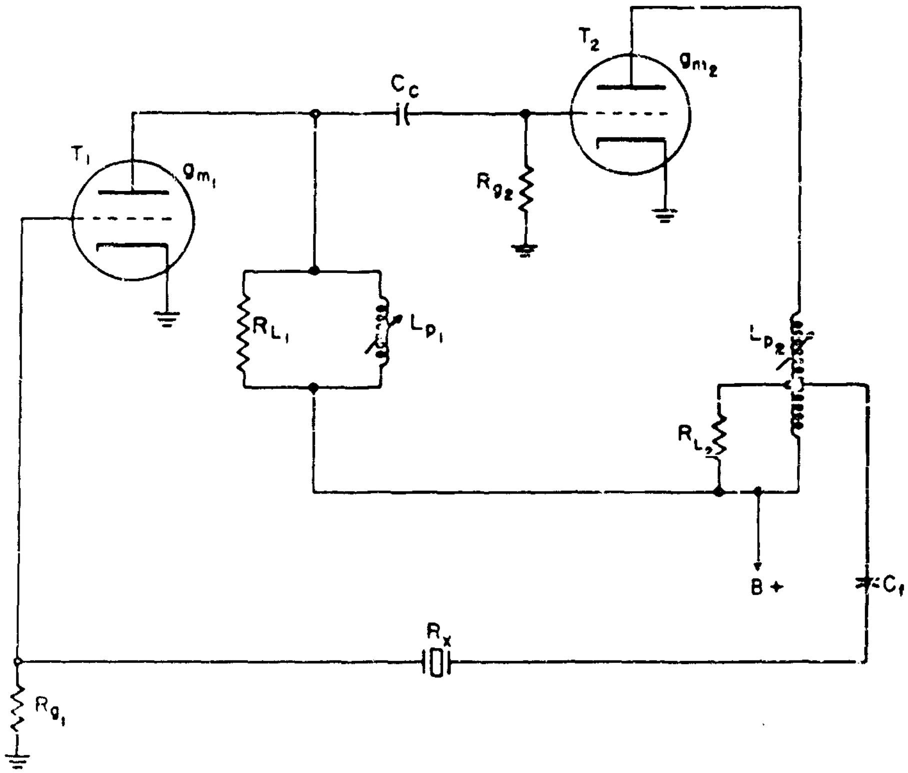


FIG. 28 —— FEEDBACK OSCILLATOR.

the crystal, as is the combination of L_{p1} and the stray capacitances due to the plate circuit of the first tube and the grid circuit of the second tube.

The loop gain is given by

$$G = A_1 A_2 A_x / N_{p2} \tag{32}$$

where A_1 is the voltage gain of the first amplifier stage, A_2 is the voltage gain of the second amplifier stage, A_x is the ratio of the first amplifier input voltage to the tap voltage and N_{p2} is the ratio of the second amplifier output voltage to the tap voltage.

The individual voltage gains are given in the following expressions; where the tube and circuit parameters are transconductance of the first triode amplifier tube, g_{m1}; transconductance of the second triode tube, g_{m2}; the load of the first stage, including all plate circuit losses of the first stage and grid circuit losses of the second stage, R_{L1}; the total load in the second stage R_{L2}; the series resonant resistance of the crystal unit R_x; and the total of all grid circuit losses in the first stage, R_{g1}.

The gain of the first triode stage is $g_{m1} R_{L1}$. The gain of the second triode stage is given by $g_{m2} N_{p2}^2 R_{L2}(R_x + R_{g1})/(R_{L2} + R_x + R_{g1})$. The tap voltage is simply the output of the second triode multiplied by $1/N_{p2}$. The input to the first triode is $R_{g1}/(R_x + R_{g1})$ times the tap voltage. Therefore, the expression for the loop gain is:

$$G = \frac{g_{m1} R_{L1} g_{m2} N_{p2}^2 R_{L2} (R_x + R_{g1}) R_{g1}}{N_{p2} (R_x + R_{g1}) (R_{L2} + R_x + R_{g1})} \tag{33}$$

or simplifying,

$$G = \frac{g_{m1} g_{m2} N_{p2} R_{L1} R_{L2} R_{g1}}{R_{L2} + R_x + R_{g1}} \tag{34}$$

It can be seen that increasing R_x will decrease the loop gain, but increases in any other parameter will increase the loop gain.

This circuit was developed specifically for use with subminiature filament-type tubes. However, with existing values of transconductance for these tubes, it has been found that the circuit will not oscillate. Even with the use of indirectly heated cathode tube types with g_m values of 4000 mhos operation was marginal. No advantage is offered by the Feedback oscillator for normal use, since it is more difficult to construct and adjust than the Grounded Grid and the Cathode Coupled circuits.

F. Analysis of the Capacitance Transformer Coupled Oscillator

The Capacitance Transformer Coupled oscillator is shown schematically in Fig. 29. This circuit is similar to the conventional transformer coupled oscillator, except that the feedback voltage is obtained from a tap on the plate coil and is applied through the crystal and a pi network to the grid of the tube. This pi network is an impedance and phase inverting circuit which matches the low impedance of the crystal to the high impedance at the grid. Inherent in this system is the voltage step-up from the crystal side of the network to the grid side. This step-up is approximately equal to the ratio of C_g/C_{gk}.

The loop gain equation for this circuit is:

$$G = A_a A_x \frac{N_g}{N_p} \qquad (35)$$

where A_a is the gain of the amplifier stage, A_x is the ratio of the pi network input voltage to the plate coil tap voltage, N_g is approximately the ratio C_g/C_{gk}, and N_p is the ratio of the oscillator plate voltage to the tap voltage. All loading effects are included in R_L which is shown from the tap

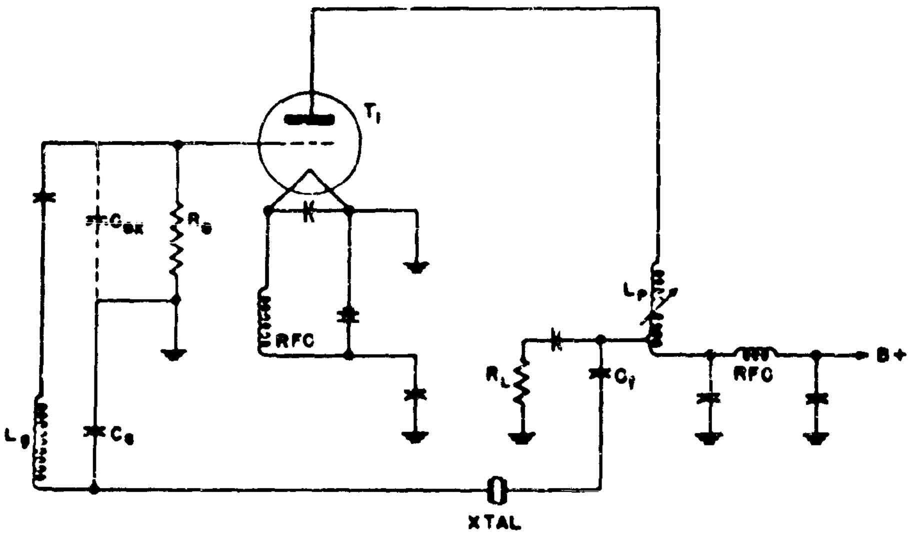


FIG. 29 — CAPACITANCE TRANSFORMER COUPLED OSCILLATOR.

to ac ground.

The effective amplifier load, for gain purposes, is the transformed impedance of R_L in parallel with the equivalent impedance looking into the crystal network from the transformer side. The individual gains are given by the following expressions:

$$A_a = \frac{g_m N_p^{\,2} R_L \,(R_x + r_g/N_g^2)}{R_x + R_L + r_g/N_g^2} \tag{36}$$

where g_m is the transconductance of the tube, R_x is the crystal resistance at series resonance, and r_g is the equivalent ac input impedance of the tube.

$$A_x = \frac{r_g/N_g^2}{R_x + r_g/N_g^2} \tag{37}$$

The loop gain, G, then is:

$$G = \frac{g_m N_p N_g R_L r_g}{r_g + N_g^2 (R_x + R_L)} \tag{38}$$

which may be compared to the equation for the loop gain of the Transformer Coupled oscillator, equation (27).

For an analysis of the pi network, Fig. 30 shows the equivalent schematic of the major components and parameters. The input voltage, e_1, is measured from crystal to ground, e_g is the voltage from grid to ground, r_g is the ac input impedance of the tube, C_{gk} is the stray capacity from grid to ground, C_g is a physical capacitor in addition to the crystal-to-ground strays, and L_g is the grid coil which tunes to the series resonant frequency of the crystal with the series combination of C_{gk} and C_g.

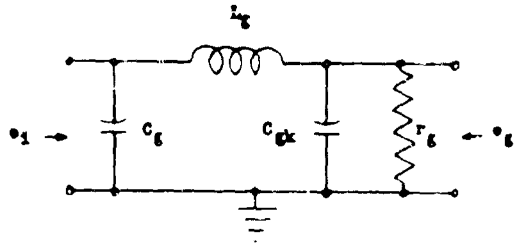


Fig. 30 - Equivalent Circuit of the Pi Network

The ratio e_g/e_1 ($= N_g$) is

$$N_g = \frac{-C_g}{C_{gk} + \left(\frac{C_{gk} + C_g}{j\omega r_g C_{gk}}\right)} \tag{39}$$

If r_g is large compared to the reactance of a capacitor equivalent to the series combination of C_{gk} and C_g, the second term in the denominator can be neglected and (39) reduces to

$$N_g = -C_g/C_{gk} \tag{40}$$

The presence of r_g results in a phase shift of less than 180°, as evidenced in equation (39), and the crystal will operate at a frequency different from f_s to compensate for this.

To lessen the effect of the imaginary term in (39), it is necessary to increase the value of one, or possibly all, of the components involved in this term. Since the value of r_g is limited by the characteristics of the tube and the bias resistor in the grid circuit, suitable values of C_{gk} and C_g

must be used. The ratio of the real to the imaginary parts of equation (39) is,

$$\frac{\text{Real}}{\text{Imaginary}} = \frac{\omega r_g C_{gk}^2}{C_{gk} + C_g} \tag{41}$$

To make this ratio as large as possible, C_{gk} may be increased by adding capacitance across the grid strays. The limiting value of C_{gk} is determined by the size of the physical coil needed to tune the grid circuit.

It can be seen that the loop gain, equation (38) is maximum at some value of N_g. This occurs where

$$N_g = \sqrt{r_g/(R_x + R_L)} \tag{42}$$

and the maximum value of gain is then

$$G_{max} = \frac{g_m N_p R_L}{2} \sqrt{\frac{r_g}{(R_x + R_L)}} \tag{43}$$

Using typical circuit parameter values, G_{max} for this circuit ranges in value from 2.0 to 4.0. The only frequency-dependent parameter in equation (43) is r_g. However, G_{max} is proportional to the square root of r_g, and thus is not as frequency-dependent as might be expected.

The crystal drive level is a function of the plate coil tap voltage and the impedance of r_g reflected into the crystal circuit. This is determined by the capacitance ratio, N_g.

The effects on loop gain of the various circuit parameters are listed below:

a. Increases in N_g decrease the loop gain and output, provided N_g is greater than the value shown in equation (42).

b. Increasing the grid bias resistance increases r_g and N_g and lowers the available output.

c. Maintaining a constant capacitance ratio and increasing C_{gk} and C_g, N_g increases, lowering the output.

The three variations listed above all have the effect of improving the phase characteristic of the pi network with the result that the circuit operates closer to the series resonant frequency of the crystal with a corresponding loss in output. This loss may be compromised by increasing g_m, N_p, or R_L.

IV. EXPERIMENTAL CIRCUIT OPERATING CHARACTERISTICS

With the development of the equivalent circuits and the loop gain equations, given in the preceding section, comparative performance measurements were made and the results are presented and discussed here for the Grounded Grid, Cathode Coupled, and Capacitance Transformer coupled circuits. In order to obtain information for devising a design technique for these oscillator circuits in the frequency range of 75 to 150 mc, circuit component values were varied and the resulting changes in circuit performance were tabulated and graphed. Use of these graphs allowed the choice of a circuit arrangement having the most desirable performance characteristics.

To determine the changes in circuit performance with variations of circuit components, a reference circuit for each oscillator at the various frequencies was chosen. In general, the reference circuit represents optimum conditions of operation. In the graphs to follow, the basic circuit schematic is shown with appropriate component symbols and the values of the reference circuit components are included.

Component changes were effected on this reference circuit and the changes in oscillator performance plotted. In general, the plate supply voltage was plotted as the abscissa with the ordinate representing two parameters: the output voltage, e_o, and the crystal driving power, P_x. Curves were obtained by holding all but one component constant at the reference circuit values and varying this one through a range.

Circuit layout materially effects the performance of an individual oscillator. However, selection of proper components is also critical. As reported in Section II, good grounding is the major layout concern. The centerposts of the tube bases were used as the primary grounding sources, keeping all lead lengths as short as possible.

A. Performance Characteristics of the Grounded Grid Oscillator

The preliminary reference circuit of the Grounded Grid oscillator is shown in Fig. 31. Component values are indicated on the schematic. These values were selected to insure oscillator operation throughout the range of frequencies and plate supply voltages used, but are somewhat arbitrary. By means of varying one component through a range of values and keeping the others fixed, plots of performance variations were made. The resulting graphs were analyzed and a reference circuit was determined which would produce optimum operational characteristics. This circuit was evaluated at frequencies of 75, 105, 135 and 150 mc.

A typical set of graphs is shown in Figs. 31 through 38 for the Grounded Grid oscillator operating at 105 mc. These figures show performance variations with changes in g_m, R_x, R_L, R_k, R_g, C_f, and tap point of the plate coil. Using the loop gain analysis results for comparison, it can be seen, from equation III-4, that the output increases for increasing values of N, R_L, and g_m. The experimental results shown in Figs. 32, 34, and 38, for variations in g_m, R_L, and Δt, respectively, verify this conclusion. Increasing the tap point (which is defined as Δt, the incremental increase in the number of turns from the initial tap point away from the ground end of the coil) places a higher voltage at the input of the crystal and also at the input circuit of the tube, raising the output and drive level. In addition, increasing the value of R_x will reduce the output, as shown from the loop gain equation and verified by the results in Fig. 33. Increasing the bias voltage on the tube will decrease the transconductance and, consequently, the output. This is shown in graphs of Figs. 35 and 36. Although C_f is not a critical circuit parameter, the variations in performance produced by changes in this component are shown in Fig. 37. The selection of the proper value of this component

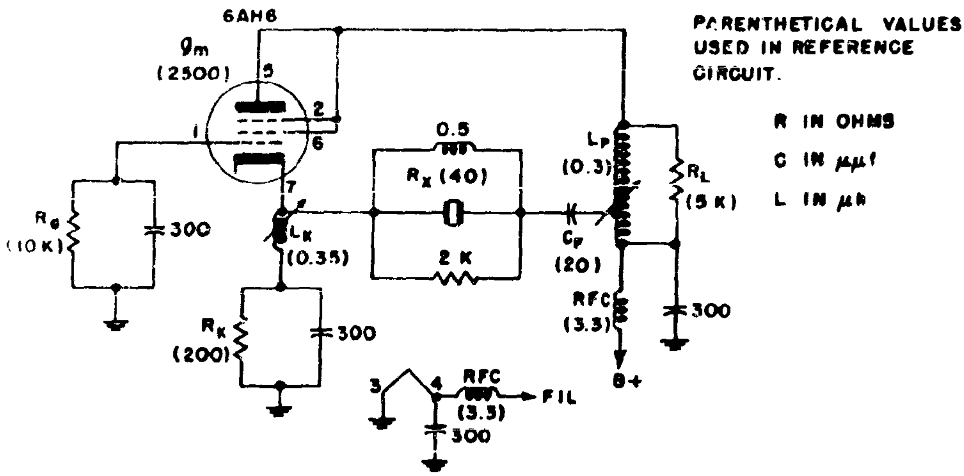


FIG. 31 —— GROUNDED GRID OSCILLATOR AT 105 mcs.

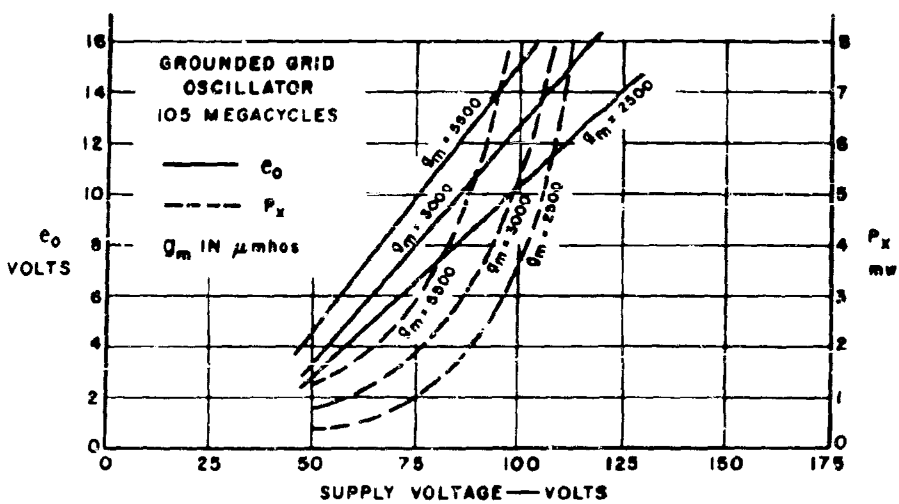


FIG. 32 —— CIRCUIT PERFORMANCE WITH CHANGES IN g_m.

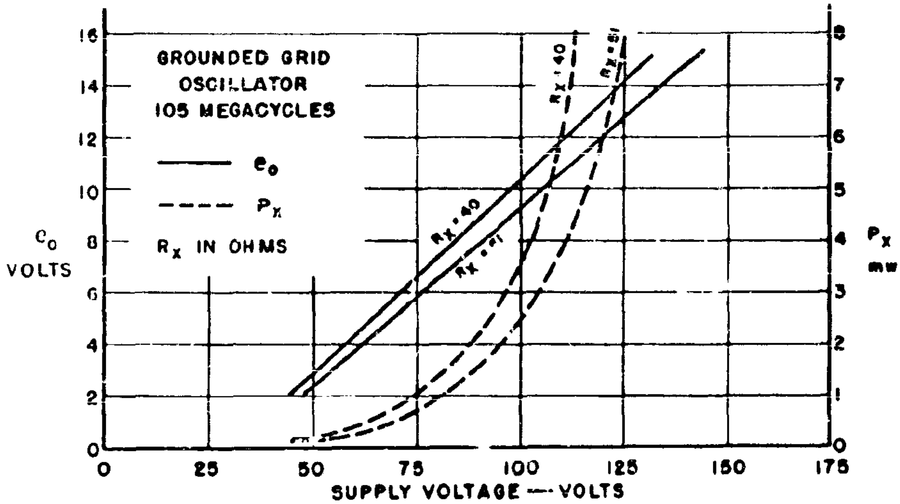


FIG. 33——CIRCUIT PERFORMANCE WITH CHANGES IN R_X.

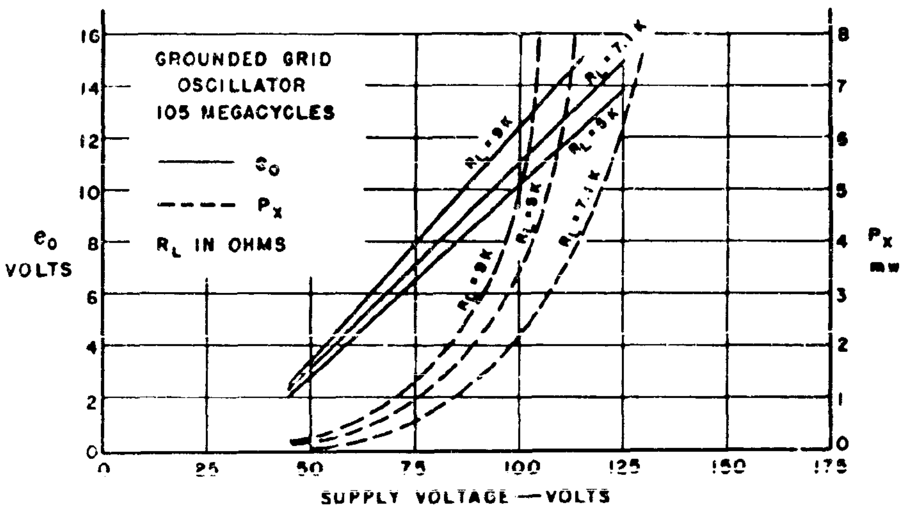


FIG. 34— CIRCUIT PERFORMANCE WITH CHANGES IN R_L.

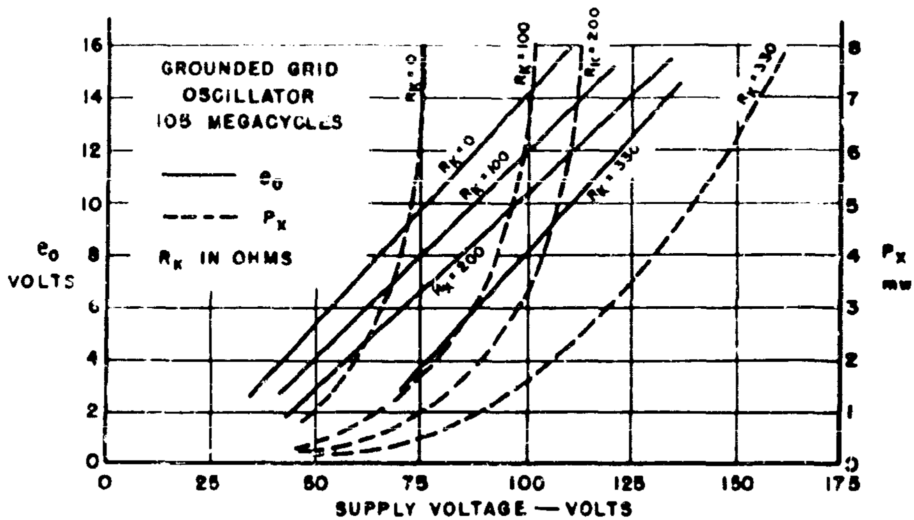


FIG. 35—CIRCUIT PERFORMANCE WITH CHANGES IN R_K.

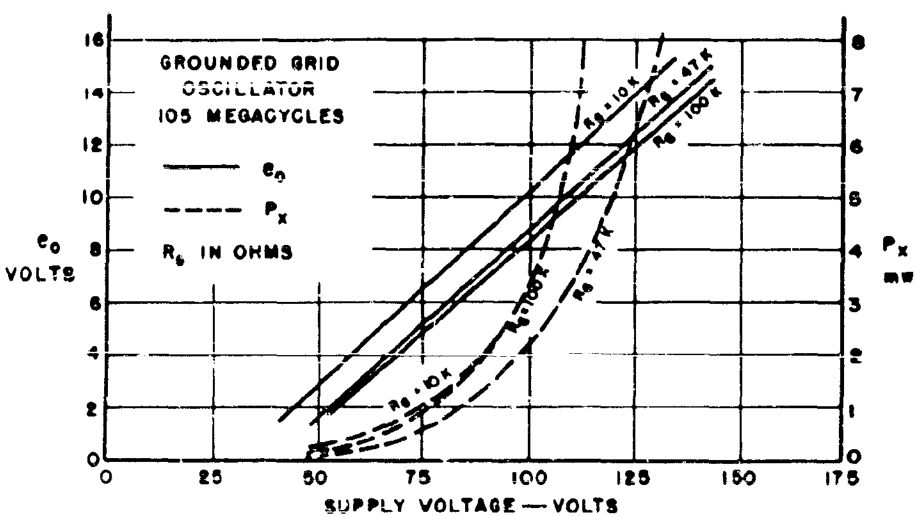


FIG. 36 —CIRCUIT PERFORMANCE WITH CHANGES IN R_G.

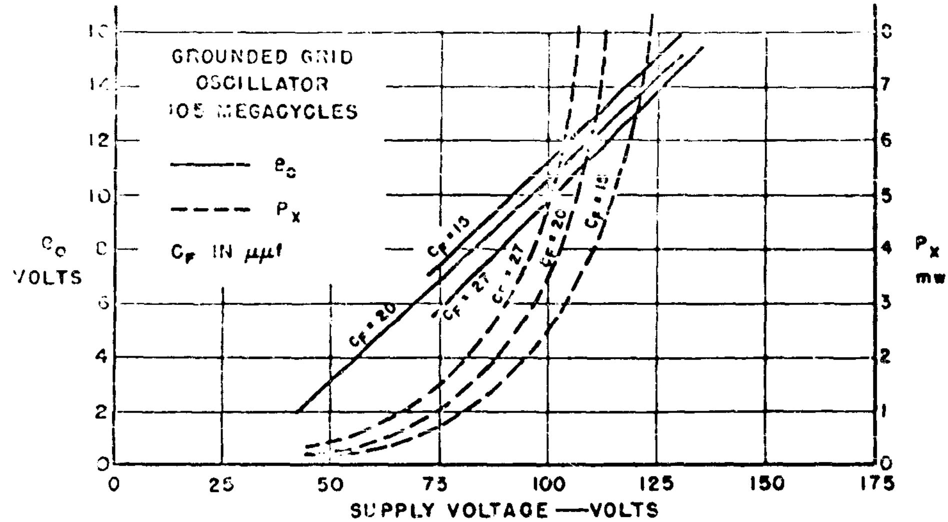


FIG 37 — CIRCUIT PERFORMANCE WITH CHANGES IN C_F.

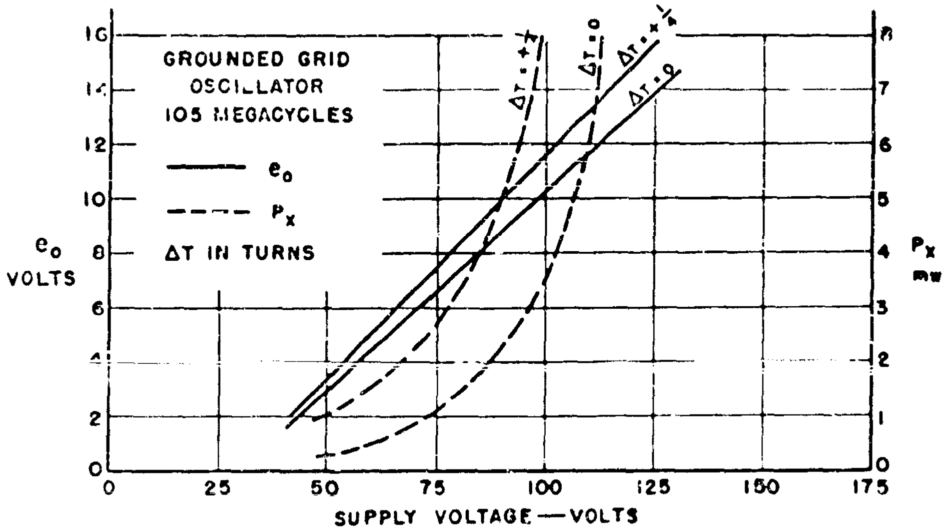


FIG. 38 — CIRCUIT PERFORMANCE WITH CHANGES IN TAP POINT

depends on the leakage inductance of the plate coil that appears at the tap and is chosen to resonate with this inductance at the series resonant frequency of the crystal.

Selection of the component values for the finalised reference circuit requires an evaluation of the performance graphs of the oscillator operating throughout the entire frequency range. This evaluation was accomplished, being based on such performance characteristics as output voltage, crystal drive level, power ratio, frequency correlation, and frequency stability with changes in plate supply voltage. The resulting reference circuit, given in a later section, is then used in the development of the design method.

B. Performance Characteristics of the Cathode Coupled Oscillator

The preliminary reference circuit of the Cathode Coupled oscillator is shown in Fig. 39. This circuit was experimentally evaluated at frequencies of 75, 105, 135, and 150 mc. Typical performance graphs are shown for operation at 105 mc in Figs. 40 through 46. These figures show performance as a function of the values of g_m, R_x, R_L, R_{kg}, R_{gg}, and R_{gc} (see circuit schematic for components associated with these symbols). To compare the theoretical considerations with the experimental results obtained here, reference is made to the loop gain equation for the circuit indicated by equation III-9.

The expected increase in output with increasing values of g_m and R_L is shown by inspection of the graphs in Figs. 40 and 42, respectively. Output decreases with increasing values of R_x as verified by Fig. 41. The bias components of the grounded grid stage, R_{kg} and R_{gg}, lower the transconductance of the tube with increasing value of resistance. Hence, the output decreases, as indicated in the graphs of Figs. 43 and 46, respectively. Increasing the resistance of R_{kc} lowers the transconductance of the tube; however, the output

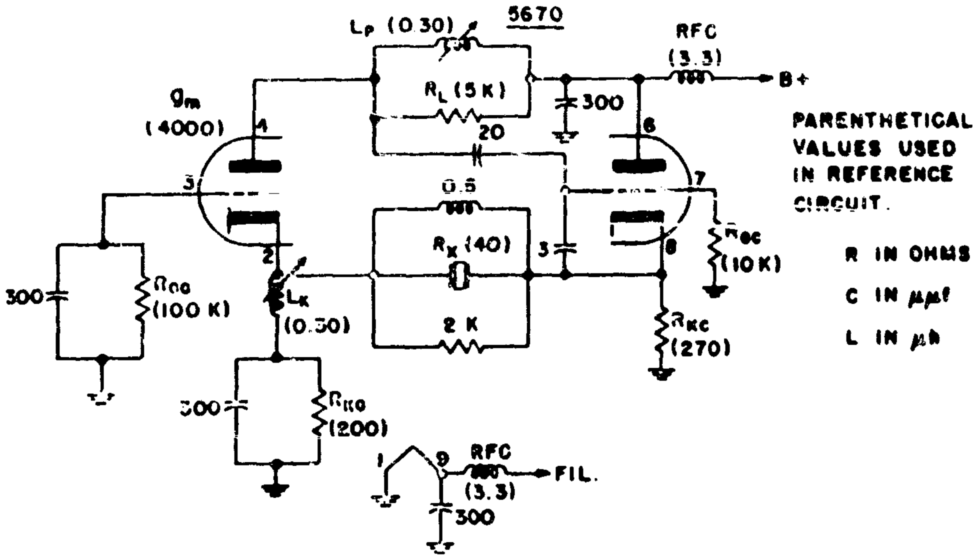


FIG. 39—CATHODE COUPLED OSCILLATOR AT 105 mcs.

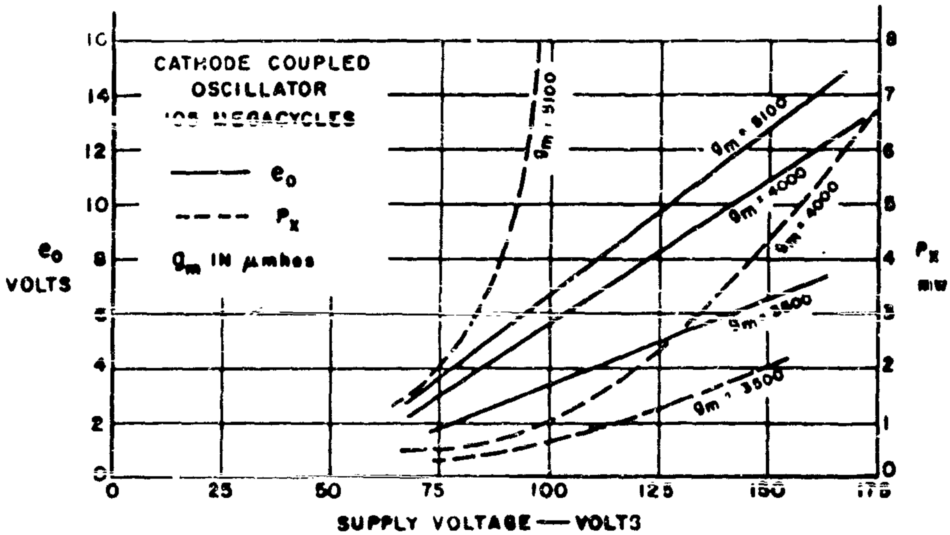


FIG. 40—CIRCUIT PERFORMANCE WITH CHANGES IN g_m.

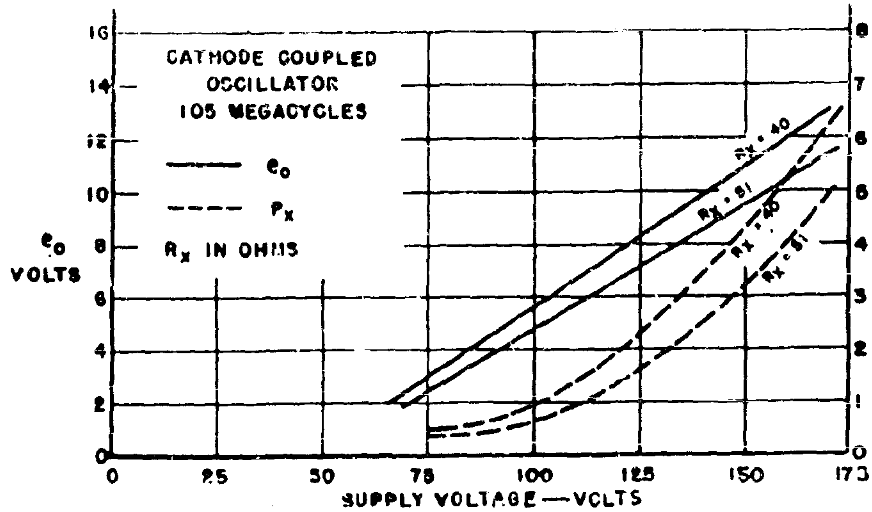


FIG. 41 —CIRCUIT PERFORMANCE WITH CHANGES IN R_X.

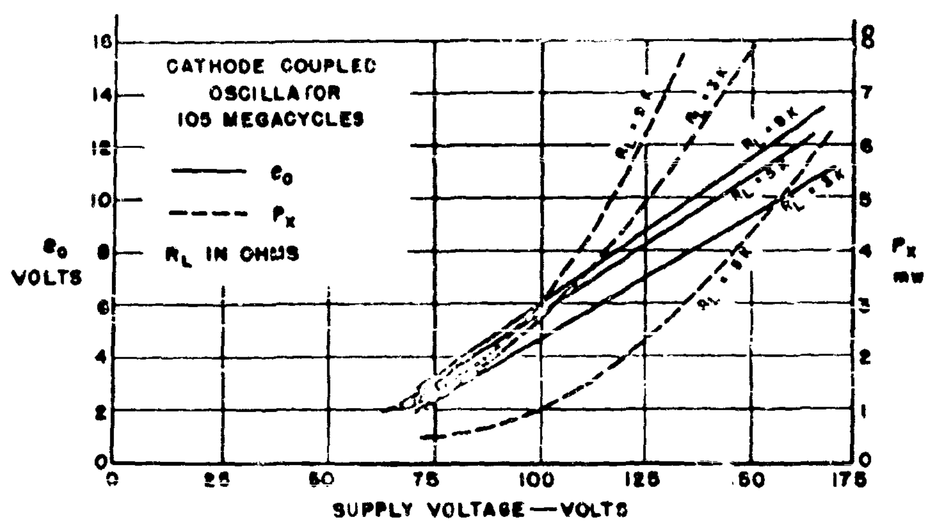


FIG. 42 —CIRCUIT PERFORMANCE WITH CHANGES IN R_L.

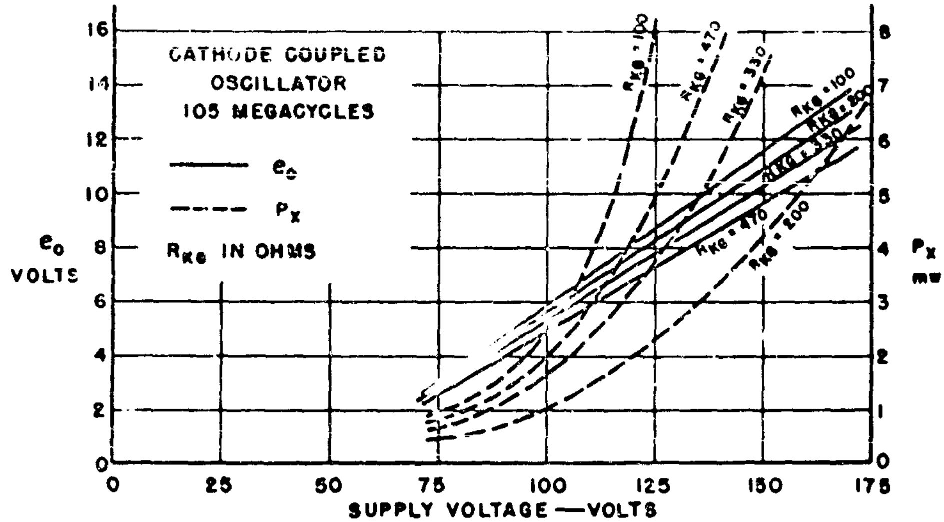


FIG. 43 — CIRCUIT PERFORMANCE WITH CHANGES IN R_{KG}

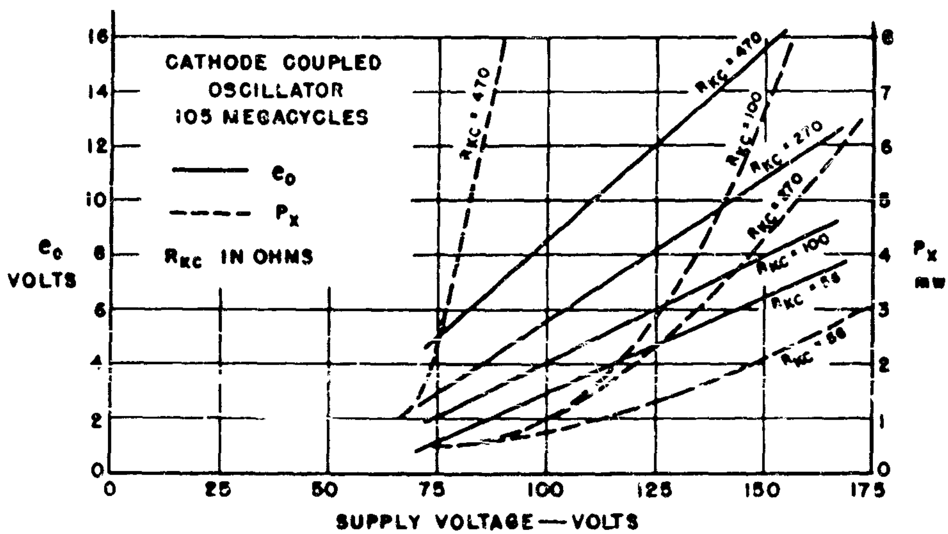


FIG. 44 — CIRCUIT PERFORMANCE WITH CHANGES IN R_{KC}

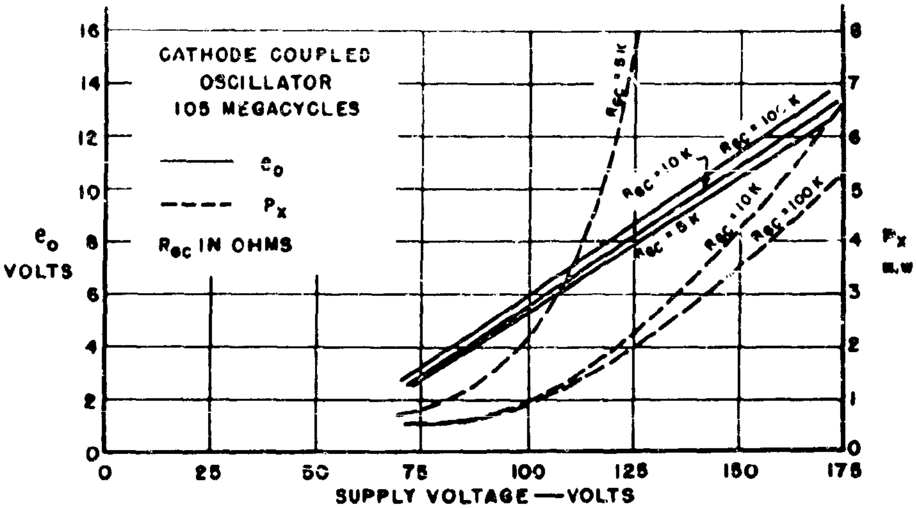


FIG. 45 — CIRCUIT PERFORMANCE WITH CHANGES IN R_{GC}.

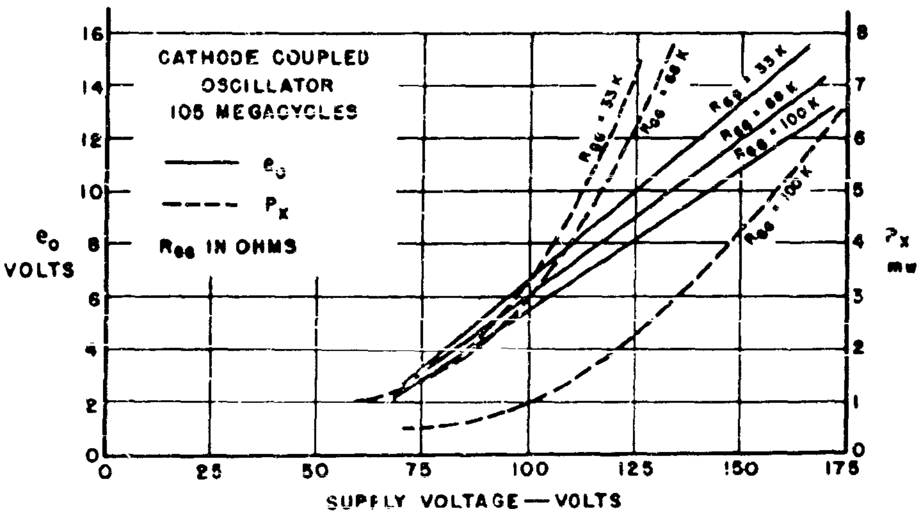


FIG. 46 — CIRCUIT PERFORMANCE WITH CHANGES IN R_{GG}.

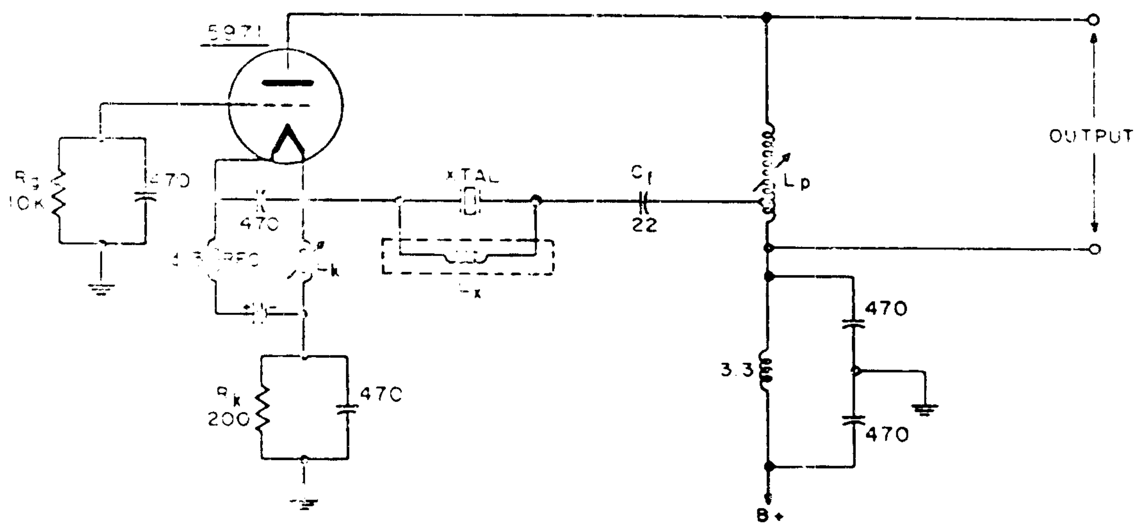
impedance of this stage is such that the level of feedback is greater, tending to increase drive and output, as shown in Fig. 44. It can be seen that R_{gc} is actually part of the output loading. Hence, increasing this component value would decrease the loading and increase output. This is verified by the results shown in Fig. 45.

By evaluating the results thus obtained for operation over the frequency range and plate supply voltages used, a finalized reference circuit was established, which was used as a basis for the design method.

C. Performance Characteristics of the Grounded Grid Subminiature Tube Oscillator

An investigation of performance of the Grounded Grid oscillator with the use of tubes having directly heated cathodes has been made. The circuit diagram is shown in Fig. 47. Operational characteristics at 75 and 105 mc are found in Tables XV and XVI.

This circuit could not be made to oscillate as a true crystal controlled oscillator because of the low tube transconductance and the resulting low loop gain. However, it is included here as a useful circuit for certain applications. Experiments indicated that oscillation could be obtained if another feedback path is provided. This path consists of the plate-to-cathode and cathode-to-ground capacitances. If the latter is completely compensated, no oscillations will occur. However, if the cathode circuit is adjusted so that a small effective capacitance appears from cathode-to-ground, oscillations will start. Adjustment of the circuit can be made such that the crystal must be present to sustain oscillations resulting in a crystal stabilized oscillator, but one of poorer stability than that of a true crystal controlled oscillator.



R IN OHMS
C IN $\mu\mu f$
L IN μh
UNLESS OTHERWISE SPECIFIED

SEE TEXT FOR DISCUSSION ON VALUES OF L_p, L_x, AND L_k.

FIG. [illegible] — GROUNDED GRID SUBMINIATURE TUBE OSCILLATOR
75 – 150 MC

R_x ohms	B+ volts	P_x mw	P_o mw	P_o/P_x -	Δf_a ppm	Δf_b ppm
	100	1.0	25.1	25.1	-14.8	2.4
22	125	2.8	54.4	19.4	-12.3	-
	150	4.1	102.1	24.9	- 4.5	-
	100	1.0	12.8	12.8	-13.2	2.6
60	125	1.5	30.0	20.0	-15.0	-
	150	2.0	64.8	32.4	+ 2.3	-

TABLE XV - PERFORMANCE CHARACTERISTICS OF THE GROUNDED GRID SUBMINIATURE TUBE OSCILLATOR AT 75 mc

R_x ohms	B+ volts	P_x mw	P_o mw	P_o/P_x -	Δf_a ppm	Δf_b ppm
	50	0.3	2.5	8.3	- 2.0	-
40	75	2.3	20.0	8.7	+11.7	-
	100	6.3	54.5	8.7	+20.3	8.6
	50	0.2	2.5	12.5	- 1.3	-
51	75	1.8	20.0	11.1	+ 0.1	-
	100	5.0	51.2	10.2	+10.3	8.1

TABLE XVI - PERFORMANCE CHARACTERISTICS OF THE GROUNDED GRID SUBMINIATURE TUBE OSCILLATOR AT 105 mc

In addition, measurements of crystal drive are not realistic because of the additional phase characteristic introduced. The voltage developed at the cathode impedance is the sum of that developed by the crystal network and the plate-to-cathode and cathode-to-ground capacities. As a result, indicated crystal drive levels are low.

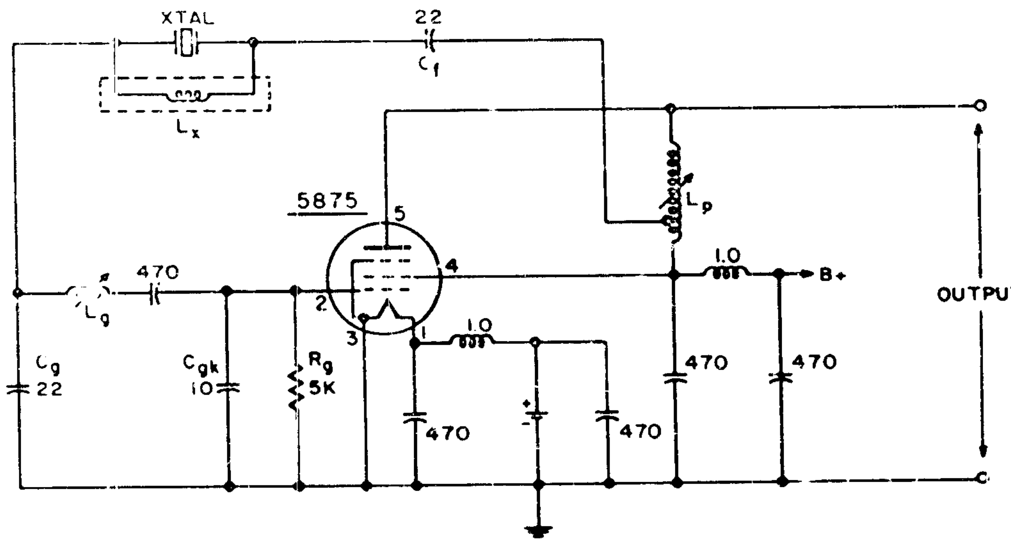
Design information, as such, was not developed for this circuit because of its limited use. However, general design procedures are similar to those of the Grounded Grid circuit using indirectly heated cathode tube types. Refer to Appendix I, Part A.2. for coil winding data, etc.

D. Performance Characteristics of the Capacitance Transformer Coupled Oscillator

During the course of investigating circuits for operation with directly heated cathode type tubes, the Capacitance Transformer Coupled oscillator was developed. As discussed in the previous section on circuit analysis, the impedance matching effected from the crystal to the grid circuit and the inherent voltage step-up of the pi network provides desirable performance characteristics for this circuit.

The schematic of the circuit is shown in Fig. 48. Performance has been determined over the 75 to 150 mc frequency range. These characteristics are found in Table XVII. Use of this circuit with filament type tubes, instead of the Grounded Grid oscillator, is recommended since the output is crystal controlled, rather than crystal stabilized.

The recommended oscillator circuit uses a 5875 subminiature pentode with a nominal g_m of 2500 μmhos. The nominal load resistance is 5000 ohms. Coil winding information for L_g and L_p, in addition to the crystal compensating inductance, L_x, is presented in Fig. 49 and Table XVIII. However, L_g may be



R IN OHMS
C IN $\mu\mu f$
L IN μh
UNLESS OTHERWISE SPECIFIED

FIG. 48 — CAPACITANCE TRANSFORMER COUPLED OSCILLATOR
75 – 150 MC

Freq. mc	R_x ohms	B+ volts	e_o volts	P_o mw	P_x mw	Δf_s ppm	Δf_t ppm
75	22	60	4.5	4.0	0.9	- 7.3	-
		75	6.9	9.4	1.6	- 2.3	-
		90	9.6	18.5	2.3	+ 0.5	4.0
	40	60	5.0	4.9	1.0	- 2.0	-
		75	7.7	11.9	2.0	+ 4.4	-
		90	10.6	22.5	3.7	+ 8.0	3.8
105	30	60	3.2	2.0	0.7	- 0.4	-
		75	5.5	6.1	2.6	+ 9.6	6.6
		90	9.7	19.0	5.3	+16.6	-
	40	60	2.8	1.6	0.5	- 5.9	-
		75	5.4	5.7	2.0	+ 7.1	5.9
		90	9.4	17.7	6.8	+16.4	-
135	40	75	4.6	4.1	2.0	- 5.5	1.9
		90	6.6	8.6	2.3	+ 6.6	-
	68	75	4.6	4.1	1.2	- 7.8	1.6
		90	6.6	8.6	1.3	+ 1.7	-
150	53	75	4.2	3.6	1.4	-11.3	3.6
		90	6.1	7.5	2.5	+ 7.2	-
	82	75	4.1	3.3	0.6	- 4.3	[illegible]
		90	5.6	6.3	1.4	+ 3.5	-

TABLE XVII - PERFORMANCE AND STABILITY CHARACTERISTICS OF THE CAPACITANCE TRANSFORMER COUPLED OSCILLATOR

75 - 150 mc

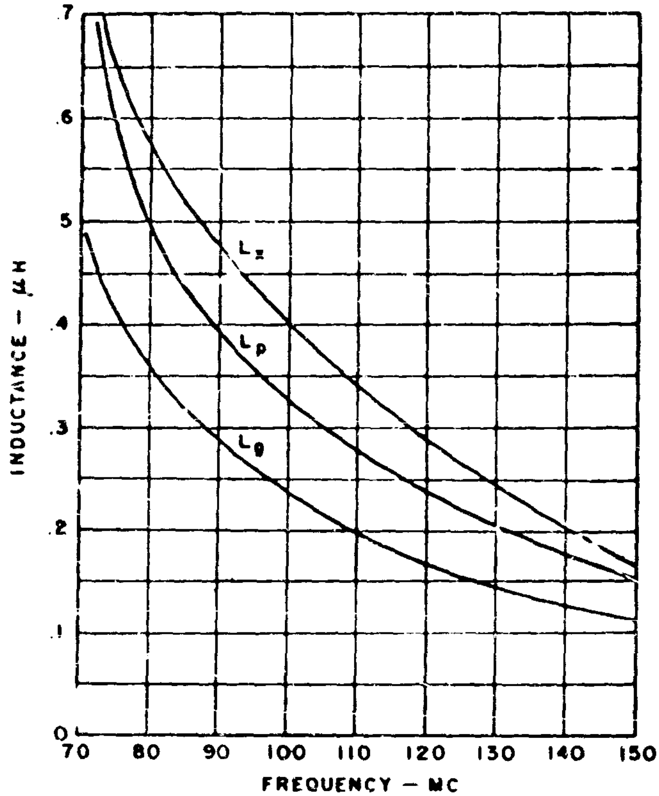


FIG. 49 — INDUCTANCE VS. FREQUENCY FOR THE CAPACITANCE TRANSFORMER COUPLED OSCILLATOR COILS
75 - 150 MC

Freq.	Coil	Coil Form	Wire Size	Coil Length	Turns	Tap	L	Q
mc	-	-	Gage	inches	-	turns	μh	-
	L_x	-	32	1/4	21	-	.670	10
75	L_g	LS6-O	20	3/8	7	-	.410	85
	L_p	LS6-O	20	3/8	8	1/2	.570	100
	L_x	-	27	1/4	16	-	.370	5
105	L_g	LS6-O	20	1/2	5	-	.210	80
	L_p	LS6-D	20	1/2	7	1/2	.300	110
	L_x	-	24	3/8	10	-	.[illegible]10	25
135	L_g	LS6-O	20	3/8	4	-	.140	70
	L_p	LS6-O	20	1/2	6	3/4	.100	100
	L_x	-	24	5/32	8	-	.360	33
150	L_g	LS6-D	20	1/2	4	-	.110	50
	L_p	LS6-O	20	1/2	5	3/4	.160	60

NOTE: L_x is wound on a 2K, 1/2 watt carbon composition resistor. The indicated coil types for L_g and L_p are Cambridge Thermionic Corp. forms, 0.26" O.D., 27/32" long. LS6- is the part number specifying the coil form type and size. The suffix designates the core formulation.

The tap on L_p is measured from the ground end of the coil.

The inductance and Q of all crystal coils, L_x, were measured at 50 mc on the Boonton Radio Corp. Q Meter, Model 160A. The inductance and Q of L_g and L_p were measured at their operating frequencies on the Boonton Radio Corp. Q Meter, Model 170A.

TABLE XVIII - CAPACITANCE TRANSFORMER COUPLED OSCILLATOR COIL DATA

75 - 150 mc

either tunable or fixed. The winding data is to be used as a guide in selecting the proper inductance of the coils, although following the exact configuration is not necessary.

Initial tuning adjustments of the circuit are as follows. L_x is wired across the crystal socket terminals and all other connections to this socket are removed. With the crystal plugged into the socket, the coil is adjusted to resonate with C_o of the crystal, at the crystal frequency. This may be accomplished with a grid dip meter (Measurements Corp. Model 58 Megacycle Meter, for instance). The correct value of inductance is indicated when the dip coincides with the activity peak of the crystal unit, although this adjustment is not critical. When L_x has been tuned, the crystal is removed from the socket and one side of L_x is opened. All other normal connections are wired to the crystal socket and filament power is applied to the tube. The plate supply voltage is left off. L_g is then tuned by use of a grid dip meter to the nominal crystal frequency, f_n. At this point, L_p may be approximately tuned by the same procedure. L_x is rewired on the crystal socket and with the crystal in place, the supply voltage is applied. L_p is now adjusted for maximum output voltage and the procedure is complete.

Several component and circuit parameter changes may be effected to obtain specific performance characteristics. The more obvious methods of raising output voltage are to increase the load resistance or lower the bias on the tube. Another method that may be used is to raise the coil tap point. The selection of the proper tap point affects the drive level of the crystal, and is thus limited in range in order to keep the power dissipation within prescribed limits. In addition, since output is a function of the ratio of C_g to C_{gk}, it can be seen from the loop gain analysis (equations III-38 and III-40) that increasing C_{gk}, by padding the grid-to-ground capacitance, will result in higher output. However, crystal drive will also increase. Therefore, the ratio should not be greater than 3 or 4 to one. Another limiting factor on this ratio is the physical size of L_g needed to resonate the total capacitance at the desired frequency of operation.

Although the 5875 tube is used in portable equipment where space requirements are critical, another type, the 6612, is a subminiature filament-type pentode that utilizes a "B" supply of 50 volts and provides output comparable to that of the 5875. The nominal g_m of the 6612 is about 2200 μmhos.

V. DEVELOPMENT OF THE DESIGN METHOD

With the determination of the performance of the Cathode Coupled and Grounded Grid oscillators, and the development of a reference circuit for each oscillator that operates over the required frequency range and plate supply voltages, it was necessary to investigate the operation of the oscillator circuits over a wide range of conditions. The result of this investigation led to the establishment of a set of design criteria for each circuit type, which, in turn, was coordinated into a complete design method.

Performance curves for the two series resonant circuits were presented in the previous section. In order to obtain correlated data, the generalized reference circuits were subjected to a wide variety of component and circuit parameter changes and the resulting performance data evaluated with the aim of generalizing this information and deriving a set of design criteria.

The initial approach was made by interpolating the performance curves, of which those in the previous section are typical examples. By varying crystal resistance and load resistance at several levels of plate supply voltage, a set of curves were plotted from the data. Since the curves were essentially linear, simple equations could be obtained to describe performance. However, variation of other circuit components resulted in nonlinearities that were difficult or impractical to describe in this manner.

In order to obtain additional data with changes in tube parameters, a survey was made to determine those tube types which would satisfy circuit requirements as indicated by the loop gain equations for the Grounded Grid and Cathode Coupled oscillators (equations III-4 and III-9, respectively).

Although pentodes may be used, they are undesirable since most Mil approved types have the suppressor connected to the cathode internally, increasing the possibility of uncontrolled oscillations due to the increased plate-to-cathode capacitance. For general purpose application, it was found that the 5670 miniature dual triode was the most suitable. The transconductance of this tube type is well above the minimum required in either oscillator circuit type, where typical component values are assumed. In addition, having both triodes in one envelope is convenient for use in the Cathode Coupled circuit, and the additional triode stage for the Grounded Grid circuit can be advantageously utilized as a buffer amplifier. Other types suitable for this application are the 12AT7 and 6021, the former being a prototype of the 5670 and the latter a subminiature cathode type similar in characteristics to the 5670. In addition, two separate triodes may be used for the Cathode Coupled oscillator, provided the g_m is greater than 2000 µmhos.

Since it was desirable to simplify the use of the design method as much as possible, it became necessary to determine a single set of reference circuit components suitable for use throughout the frequency range. Performance of this circuit is then determined as a function of frequency and the effect of component value on performance is then determined and plotted as a normalized curve with respect to the performance and component value of the reference circuit. This method gives a more realistic measure of circuit operation than that attempted previously.

The only component changes necessary throughout the frequency range were the cathode coil, L_k; the plate coil, L_p; and the crystal compensating inductance, L_x. L_k and L_p are tuned to the circuit and stray capacitances in the cathode and plate, respectively. L_x is resonated with the shunt capacitance of the crystal.

The major considerations given in circuit construction were in proper grounding techniques, lead dress, decoupling, and part placement. In general, grounding was accomplished at the tube base centerposts and the power plugs. Placement of parts was determined to hold lead length to a minimum. For the test circuits output voltage was made available through a pin jack. To obtain frequency measurements, connection was made, by means of a small capacitor, from the output to a coax connector. The crystal socket was placed for insertion of the differential voltmeter probe, described in Section II. Decoupling was accomplished with commercially available inductances and capacitors. It was found that 470 mmfd disc ceramic capacitors were suitable for use throughout the frequency range. Plate decoupling coils were generally 3.3 μh and filament decoupling coils were 1.0 μh for most circuits.

With the establishment of the reference circuit, component variations were made and the resulting performance was plotted. These performance characteristics were output voltage, e_o; crystal drive voltage, e_x; the correlation between circuit operating frequency and the series resonant frequency of the crysta , Δf_s; and the frequency stability of the circuit with changes in supply voltage, Δf_b, and filament voltage, Δf_f.

Output voltage as a function of supply voltage was determined for the reference circuit at each test frequency. The sets of data were then correlated to produce the graph of output-frequency characteristics of the two oscillators. Similarly, the crystal drive voltage was measured, for the reference circuits, and plotted. Frequency characteristics of the reference circuit were determined and tabulated.

The development of the design method, once the reference circuit having the desired characteristics had been obtained, consisted mainly of varying circuit component values over a chosen range and noting the resultant effect on circuit operation. The circuit components and parameters varied were the bias resistances, crystal resistance, tube transconductance and the oscillator load resistance.

The output and crystal drive voltages were tabulated for each component value, over a range of plate supply voltages. It was found that performance is dependent on percentage component change to the same extent at all frequencies throughout the range. The information could thus be generalized without any loss of accuracy. Consequently, graphs of output versus component values were normalized with respect to the reference circuit values.

The complete design method for crystal oscillators operating over the 0.8 to 150 mc frequency range is presented in Appendix I. Part A presents complete information on the Grounded Grid and the Cathode Coupled oscillator circuits operating in the 10 to 150 mc frequency range. A complete description of these series resonant circuits is given, with respect to circuit construction, component characteristics, tuning procedure, design examples, and performance characteristics. Similar information is given for three antiresonant circuits in Part B. These are the Colpitts (Grounded Plate Pierce), Electron Coupled Colpitts, and the Miller oscillators. Basic studies of the Colpitts oscillator were completed on a previous Foundation program[1]. As a part of this program, the available information was rechecked and the frequency range extended to 20 mc. Performance information for subminiature filament type tube circuits has been presented in Section IV.

VI. SERIES RESONANT OSCILLATOR OPERATION TO 200 mc

Investigations have been made of the performance characteristics of the Grounded Grid and Cathode Coupled oscillators operating at frequencies up to 200 mc. In general, it has been found that the circuits must be operated at a higher level to sustain oscillations. Output voltage is somewhat lower and crystal drive higher than that experienced at the lower frequencies.

Crystal units were obtained from several manufacturers at the specific frequencies of 175 and 200 mc. The series resonant resistance of all units was less than 100 ohms as measured in the modified TS-683 Crystal Impedance Meter. The 175 mc units were mounted in HC-6/U holders and the 200 mc units in HC-18/U holders. The crystals operated on the ninth overtone of their fundamental frequency.

Circuit constructional details followed the form of the lower frequency oscillators. It was necessary to use extreme care in the wiring of the circuits because of stray capacitances and lead inductances. It was found that many circuit components, specifically bypass and decoupling capacitors and some RF chokes, exhibited self-resonance at the oscillator operating frequencies. Silver mica capacitors were chosen for most applications and choke coils were selected to minimize decoupling problems.

In order to obtain reasonable operation of the Grounded Grid circuit throughout the range of frequencies and plate supply voltages over which it was tested, it was found necessary to decrease the cathode bias resistance to 100 ohms. The load resistance used was 10,000 ohms. At 175 mc the output voltage developed varied from a low of 3.0 to a high of 14.0 volts as the plate supply voltage was varied from 75 to 150 volts. Crystal drive ranged from 1.0 to 8.0 mw over the same operating range. The average value of Δf_b was approximately 7.0 ppm. At 200 mc it was necessary to reduce the cathode bias resistance to zero. Here, the output voltage and crystal drive were in the same range of values as those at 175 mc. The average value of Δf_b was about 8.0 ppm.

Proper operation of the Cathode Coupled Circuit was somewhat more difficult to obtain than for the Grounded Grid. However, by making R_{kg} equal to Zero and R_{gc} equal to 100k it was possible to obtain crystal controlled operation even with the 5000 ohm load. Oscillations could not be obtained for plate supply voltages less than 100 volts with this circuit arrangement. Output voltages from 3.0 to 10.0 volts and crystal drives from 1.0 to 7.0 mw were obtained for a range of B+ of 100 to 150 volts. Frequency correlation figures were below the series resonant frequency of the crystal by approximately 10 ppm. Frequency stability, Δf_b, averaged about 10 ppm over the frequency range and plate supply voltages used. The above performance information was common to both the 175 and 200 mc circuits, although operation at 200 mc resulted in slightly less output voltage, even though the load resistance was increased to 10K ohms.

The results of the limited tests at these frequencies indicate that circuit performance follows the trends shown in the design data. However, due to the low output power and high drive characteristics obtained at 200 mc, it seems that the upper limit for conventional crystal oscillator circuit arrangements is being approached. Two possible avenues of further development are indicated. One is the use of circuits having distributed parameter components, the other would be the use of a circuit similar to the high frequency CI Meter unit followed by sufficient power gain to provide reasonable output.

VII. CONCLUSIONS AND RECOMMENDATIONS

Investigation of the performance characteristics of a variety of crystal oscillator circuits has resulted in the development of a design method for a selected group of series and antiresonant oscillators. Two series resonant circuits, the Grounded Grid and the Cathode Coupled oscillators, chosen from a group of twelve circuits, exhibited the most desirable characteristics of output voltage, crystal drive level, circuit construction and tuning, and frequency stability. Variation of circuit components and parameters over a wide range of values resulted in the determination of a set of performance characteristics which could be normalized with respect to those of a reference circuit capable of operating over the entire range of frequencies and plate supply voltages.

From the generalized information a set of graphs and tables were derived for each circuit type, which can be used to design an oscillator at any specific frequency in the range. The reference circuit, on which design changes may be made in order to obtain specific performance characteristics, is the basis of all measurements. It is recommended that this circuit be used without design changes wherever possible. However, if design changes are required, the accuracy of predicting output voltage is within 20 percent of the values indicated for specific circuit designs. Crystal drive may be predicted with an accuracy of approximately 30 percent, based on measurements of crystal voltage and assumed resistive operation of the crystal.

Three antiresonant circuits, the Colpitts or Grounded Plate Pierce, the Electron Coupled Colpitts, and the Miller oscillators, have been included in the design method. The bulk of the investigation of these circuits had been performed on a previous program, but were investigated further in order to extend the frequency range to 20 mc. Here, again, the reference circuits are recommended for use, wherever possible, without design changes. However, information is available to effect design changes, using a format similar to that of the series resonant circuits.

Design information for two circuits used for special application is also included. These circuits, the Grounded Grid and the Capacitance Transformer Coupled oscillators, utilize subminiature type tubes having directly heated cathodes. The latter circuit provides true crystal controlled operation and is recommended over the Grounded Grid circuit. However, the former circuit may prove useful in certain applications, although stability is much poorer for changes in ambient conditions.

The circuits have been designed to provide reasonable outputs and utilize sound engineering principles of operation. Performance characteristics have been optimized wherever possible to take advantage of component and parameter ratings. The design examples outlined in the Design Data section (Appendix I) were selected to show the method of maximizing output voltage while staying within prescribed limits of crystal drive power. However, to obtain other specific characteristics, such as increasing frequency stability, etc., it would be necessary to investigate circuit changes capable of producing the desired results as described in the body of this report.

Experimental evidence indicates the feasibility of using the two series resonant oscillator circuits at frequencies up to 200 mc. However, it is apparent that the upper frequency limit is being approached for conventional crystal oscillator circuit arrangements. Although performance characteristics follow the trend shown for lower frequency operation, output power is much lower and crystal drive is high. For these frequencies, it may be desirable to use circuits having distributed parameter components.

VIII. IDENTIFICATION OF KEY PERSONNEL

The following is a listing of the key personnel working on this program together with a tabulation of the approximate number of hours each man has spent on the entire project. Additional hours for other services are also listed.

Man and Title or Service	Project Hours
R. W. Bull, Supervisor	476
M. Eppley, Assistant Experimental Engineer	2214
H. E. Gruen, Associate Engineer	2056
J. S. Kurinsky, Assistant Experimental Engineer	1739
A. O. [illegible]sit, Assistant Engineer	3552
E. A. [illegible]oberts, Assistant Manager	274
Technician Services	687
Supporting Services	327
Drafting and Shop Services	622
Others	58

In the paragraphs to follow, the background and qualifications of these men are given. The period of time each man was associated with this program is indicated under his name.

R. W. Bull - Supervisor, Electronic Instrumentation Section

January, 1956 - August, 1957

Mr. Bull has been active in electronic circuit development, instrumentation systems and system component studies for over seven years. His experience includes work in the areas of temperature measurement and control, telemetering, medical electronics, and industrial inspection devices. He has developed a special instrument for use in microwave spectroscopy studies and is active in the development of transistor circuitry and test equipment. Mr. Bull holds the Bachelor and Master of Science degrees from the University of Wisconsin.

M. Eppley, Assistant Experimental Engineer

May, 1955 - November 1956

Mr. Eppley has over 16 years experience in the construction and testing of electronic devices, which includes two years service with the Army Signal Corps. He has been an active amateur radio operator since 1939, and has worked with frequency control systems for approximately four years.

H. E. Gruen, Associate Engineer

May, 1955 - August, 1957

Mr. Gruen has over seven years experience in electronic circuit design, quartz crystal applications and crystal unit development. He has participated in the various programs at the Foundation, and was responsible for the Air Force programs which included circuit design studies of anti-resonant crystal oscillators and the development of a series of standard packaged crystal oscillators. Mr. Gruen was the project engineer of this program. He holds a Bachelor of Science degree in Electrical Engineering and is following a course of study leading to the Master's degree in the evening division of Illinois Institute of Technology.

J. S. Kurinsky, Assistant Experimental Engineer

November, 1955 - August, 1957

Mr. Kurinsky has nine years experience in construction and testing of oscillator circuits and frequency control devices, including crystal units and magnetostriction resonators. He has participated in various frequency control programs carried out by the Foundation and has been especially active in crystal parameter measurements and tests.

A. O. Plait, Assistant Engineer

September, 1955 - August, 1957

Mr. Plait has been active in electronics for ten years, including five years service with the U. S. Naval Reserve as an instructor of electronics and mathematics. He has also served as assistant supervisor of a Naval Electronics Laboratory for two years. He has had four years experience in the design of high frequency circuits including crystal oscillators and FM modulation circuits. Mr. Plait holds Bachelor of Science degrees in Mathematics and Electrical Engineering and is currently pursuing a course of study leading to the Master's degree in the evening division of Illinois Institute of Technology.

E. A. Roberts, Assistant Manager, Electrical Engineering Research

May, 1955 - August, 1956

Mr. Roberts has had thirteen years of experience in the communications and instrumentation fields and has concentrated on problems specifically related to frequency control for the past nine years. He has contributed to this program primarily in a supervisory capacity. He holds a Bachelor and Master of Science degree in Electrical Engineering from Illinois Institute of Technology.

IX. LOGBOOK REFERENCES

Detailed laboratory data is recorded in ARF Logbook Nos. C4816, C5531, and C5873.

Respectfully submitted,

ARMOUR RESEARCH FOUNDATION
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APPENDIX

I

DESIGN DATA FOR CRYSTAL OSCILLATOR CIRCUITS

PART A

SERIES RESONANT OSCILLATORS

PART B

ANTIRESONANT OSCILLATORS

APPENDIX I

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APPENDIX I

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PART A

SERIES RESONANT CRYSTAL OSCILLATOR CIRCUITS

GROUNDED GRID

and

CATHODE COUPLED

10 - 75 mc

75 - 150 mc

1. THE GROUNDED GRID OSCILLATOR - 10-75 mc

a. Circuit Description

The circuit diagram of the Grounded Grid oscillator recommended for use in the 10 to 75 mc frequency range is shown in Fig. 1. Coil values and general characteristics for this circuit are shown in Fig. 2. Winding data at specific frequencies is given in Table I. These are typical values used at the test frequencies. The inset graph of Fig. 1 shows the values of the feedback capacitor C_f, which are required at the indicated frequencies throughout the range. The purpose of this capacitor is to tune out the series leakage inductance of the plate tank coil, L_p, and provide isolation of the crystal from B+. For operation over a band of frequencies a single value may be used. Frequency correlation figures will be affected and the choice must be made with this in mind. A value at the center of the operating band is recommended.

The recommended oscillator circuit, to which all performance and design data is referred, has the following component and circuit parameter values:

R_g = 10K ohms (grid bias resistor)

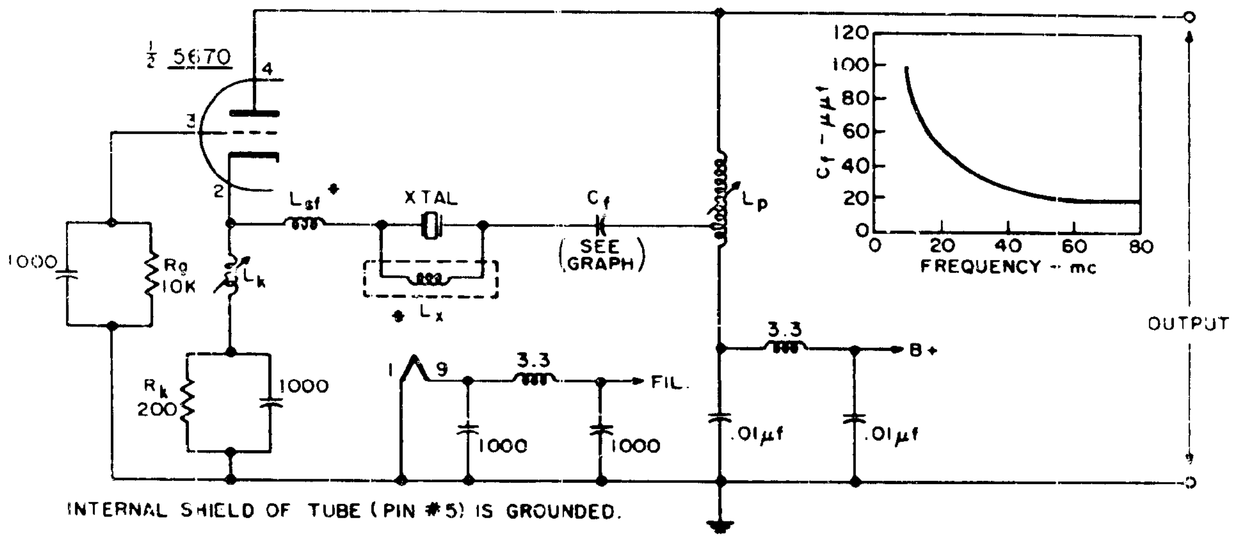
R_k = 200 ohms (cathode bias resistor)

R_L = 5000 ohms (plate load resistance)

R_x = 25 ohms (series resonant crystal resistance)

The tube type is a 5670 miniature dual triode with a nominal g_m of 5500 micromhos. The recommended bypass and decoupling component values are as shown in Fig. 1. This configuration may be altered, however, where required in a specific application. The important point is that adequate decoupl and bypassing be maintained.

It should be noted that for operation below 40 mc, L_x, which at



INTERNAL SHIELD OF TUBE (PIN #5) IS GROUNDED.

R IN OHMS
C IN μμf
L IN μh
UNLESS OTHERWISE SPECIFIED

SEE TABLE I AND FIG. 2 FOR VALUES OF L_k, L_p, L_{sf}, AND L_x.

* NOTE: L_{sf} IS NOT USED ABOVE 40mc
L_x IS NOT USED BELOW 40mc

FIG. I — GROUNDED GRID OSCILLATOR
10 - 75 MC

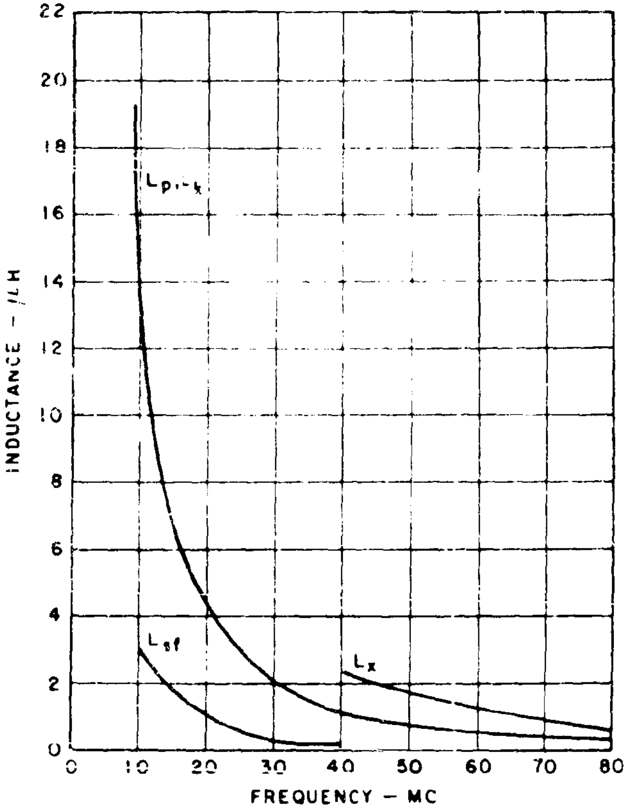


FIG. 2 —INDUCTANCE VS. FREQUENCY FOR THE GROUNDED GRID OSCILLATOR COILS 10 – 75 MC

Freq.	Coil	Coil Form	Wire Size	Coil Length	Turns	Tap	L	Q	L_s	k	L_1
mc	—	—	gage	inches	-	turns	µh	-	µh	-	µh
	L_k	LS6-E	34	5/16	47	-	17.0	60	-	-	-
10	L_p	LS5-B	32	7/8	53	10.5	16.4	60	3.9	.47	3.0
	L_{sf}	CL-1	-	1.25	-	-	2.7	-	-	-	-
	L_k	LS6-C	27	1/4	15	-	1.6	65	-	-	-
30	L_p	LS6-O	27	5/8	23	6.0	2.4	60	1.2	.46	1.0
	L_{sf}	*	21	13/32	11	-	0.4	105	-	-	-
	L_k	LS6-O	26	1/2	10	-	0.7	90	-	-	-
60	L_p	LS6-O	26	1/2	12	3.0	0.8	80	0.2	.50	.15
	L_x	-	32	1/2	15	-	1.0	5	-	-	-
	L_k	LS6-O	24	1/2	8	-	0.4	135	-	-	-
75	L_p	LS6-O	20	5/8	8	1.5	0.4	110	.04	.53	.03
	L_x	-	32	1/4	21	-	0.7	10	-	-	-

NOTE: The indicated coil types for L_k and L_p are Cambridge Thermionic Corp. forms. LS5- is 3/8" O.D., 1.063" long. LS6- is 0.26" O.D., 27/32" long. The suffix designates the core formulation. CL-1 is an International Radio Corp. molded coil. * designates a mica base form, 3/16" O.D., 3/4" long. L_x (at 60 mc) is wound on a 2K, 1 watt carbon composition resistor. At 75 mc, a 1/2 watt resistor is used. The tap on L_p is measured from the ground end.

The inductance and Q of all coils were measured at their respective frequencies on a Boonton Radio Corp. Q Meter, Model 160A.

TABLE I - GROUNDED GRID OSCILLATOR COIL DATA

10 - 75 mc

higher frequencies is used to cancel the crystal shunt capacitance. C_o, is not required. However, it is necessary to include L_{sf}, the series feedback coil, for proper frequency correlation and circuit operation. This coil is not used at frequencies above 40 mc.

b. Component and Circuit Construction Details

The recommended components are generally standard, commercially available types. This is true of all the circuits for which design data is presented, except where noted in the appropriate discussion. Resistors are standard one-half watt carbon composition types. Generally, all capacitors are disc or tubular ceramics. However, in some cases, stand-off or feed-thru ceramics may be used to advantage. In those cases where variable or high ambient temperatures are encountered it is suggested that small silver mica capacitors be used in all bypass, decoupling, and filter networks. These capacitors are available in standard sizes, and in addition, can now be obtained in "button" shapes with various mounting forms.

Tuning coils, such as L_k and L_p, and special coils, such as L_x and L_{sf}, are completely specified in the coil winding data tables and curves. Decoupling and filter coils are miniature molded types. However, where space requirements are stringent, special manufacture or hand wound coils may be necessary. It is not necessary that the coils have the exact physical configuration shown in the accompanying data. However, inductance values must be chosen to resonate with the actual circuit capacity values and must have Q's in the range of 50 to 100. The tabulated information is included to serve as a guide in selecting initial values. Since L_k is in a low impedance point of the circuit, a fixed coil may be used if the operating frequency range is not too broad. In most cases a range of 15 to 20 percent on either side of the center frequency may be covered by a fixed coil.

Standard shield base noval tube sockets are used. In order to minimize the undesirable effects of lead inductance and stray wiring capacitance, the physical layout of the circuit must be carefully designed. The use of the tube centerpost as the major grounding point is advisable.

The constructional details of the performance test circuits may be seen in Fig. 3. The photograph shows the layout of a typical 75 mc Grounded Grid oscillator. The components are labelled according to the schematic of Fig. 1. Note that L_k is a fixed inductance, as is L_x which is located beneath the crystal socket.

c. Circuit Tuning Procedure

Initial tuning adjustments are as follows. L_x is wired across the crystal socket terminals and all other connections to this socket are removed. With the crystal plugged into the socket, the coil is adjusted to resonate with C_o at the crystal frequency. This may be accomplished with a grid dip meter (Measurements Corp. Model 58 Megacycle Meter, for example). The correct value of inductance is indicated when the dip coincides with the activity peak of the crystal unit, although this adjustment is not critical. When L_x has been tuned, the crystal is removed from the socket and one side of L_x is opened. All other normal connections are wired to the crystal socket and filament power is applied to the tube. The plate supply voltage is left off. L_k is then tuned by use of a grid dip meter to the nominal crystal frequency, f_n. At this point, L_p may be approximately tuned by the same procedure. The plate coil tap point, of which nominal values are listed in Table I, was chosen, for these circuits, to provide good output to crystal drive ratios. The coil tap point is not varied as a circuit parameter since changes from the chosen

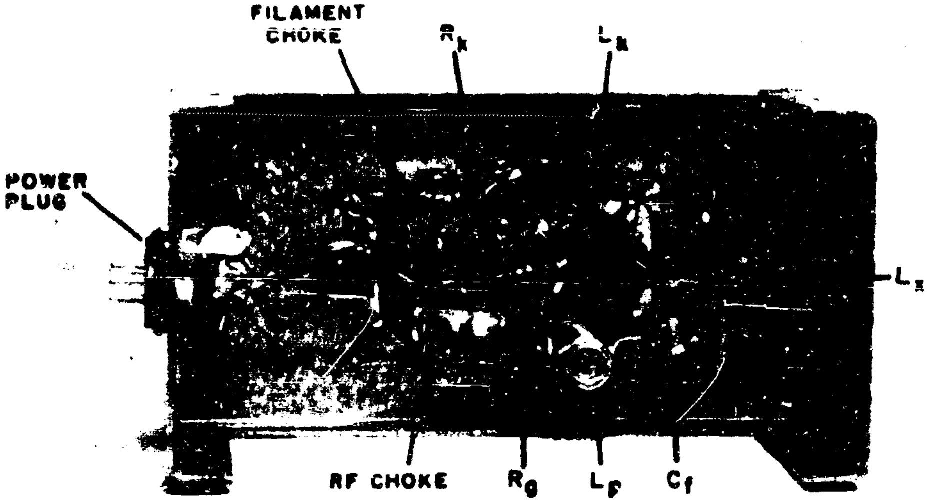


FIG. 3 —— TYPICAL GROUNDED GRID OSCILLATOR CIRCUIT LAYOUT (75 mc)

value result in decreased power ratios or poor amplitude stability. If the tap point is too close to the ac ground end of the coil, oscillations will not be obtained. If the tap point is too high, large crystal drive levels and low power ratios of power output to drive are obtained. The operating point is chosen in this range, making sure that the point is sufficiently high to obtain oscillation at all values of plate supply voltage. L_x is rewired on the crystal socket and with the crystal in place, the plate supply voltage is applied. L_p is now adjusted for maximum output voltage and the procedure is complete. The tuning indication may be obtained by direct metering of the output voltage or by adjusting the circuit for a maximum grid current or grid bias voltage. The difference in output and crystal drive resulting from either tuning method is negligible. However, the frequency is higher when the bias is used for tuning indication but is within three parts per million of that obtained by tuning to peak output.

d. Circuit Performance Characteristics

Curves of output voltage and power, and crystal drive versus frequency of operation are shown in Figs. 4 and 5, respectively. In addition, curves of required values of B+ and the resultant output for constant values of crystal drive over the frequency range are presented in Figs. 6 and 7, respectively. These graphs depict performance of a circuit having component values as indicated in Fig. 1. The performance figures obtained from changes in component value are normalized with respect to the recommended circuit figures. The resulting normalized graphs are shown in Figs. 25 through 29, on fold-out pages 55 through 59 . These graphs show output voltage, output power, and crystal drive level as a function of the values of R_L, R_g, R_k, R_x, and g_m, respectively.

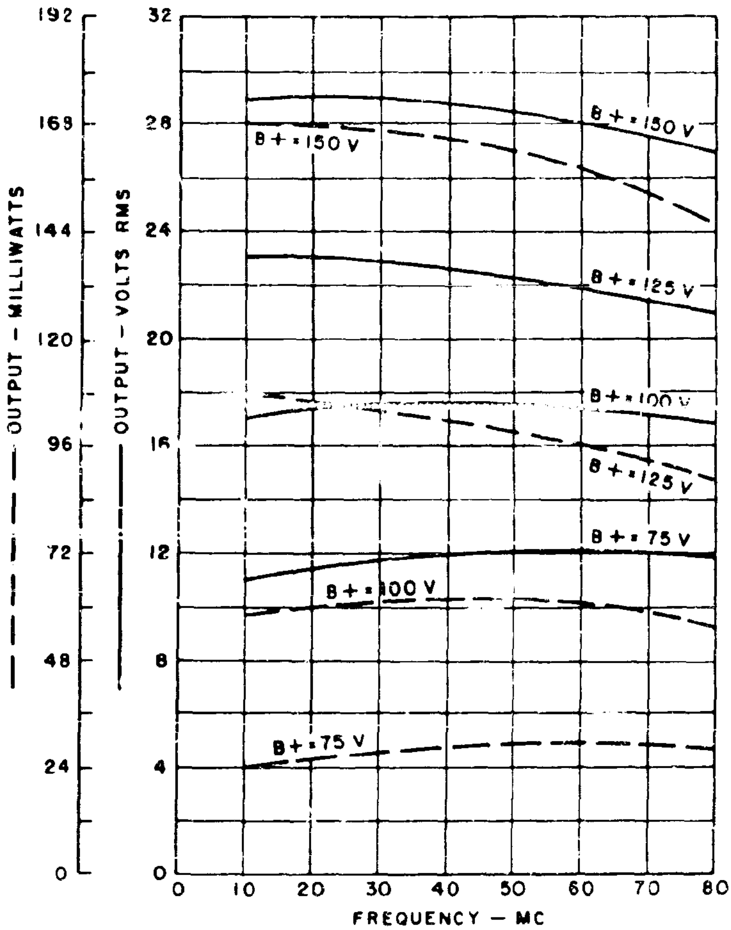


FIG. 4 — OUTPUT VOLTAGE AND POWER VS. FREQUENCY FOR THE GROUNDED GRID OSCILLATOR 10–75 MC

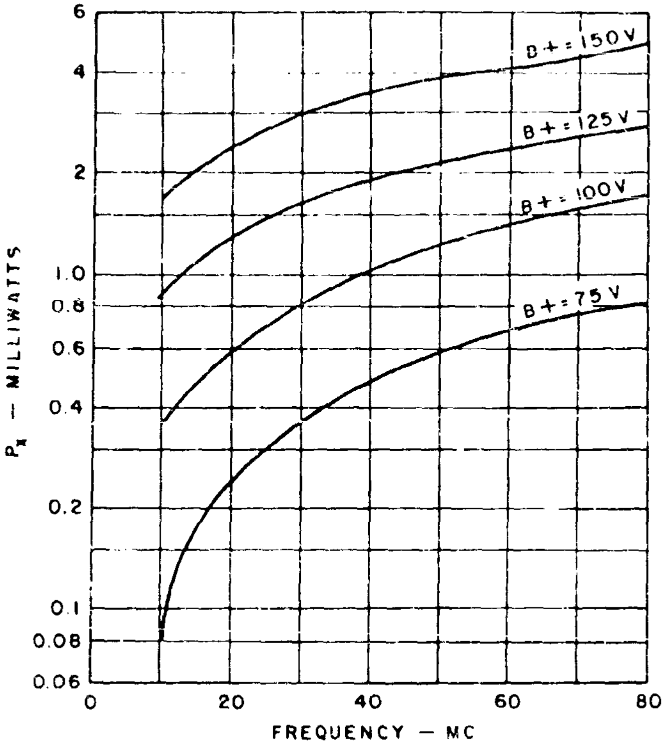


FIG. 5 — CRYSTAL DRIVE VS FREQUENCY FOR THE GROUNDED GRID OSCILLATOR 10 – 75 MC

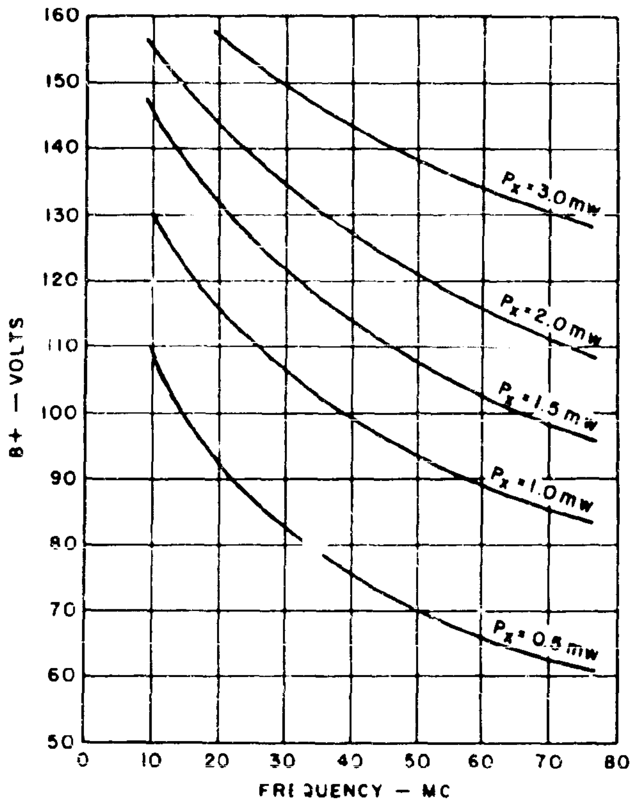


FIG. 6 B+, CONSTANT P_x CURVES FOR THE GROUNDED GRID OSCILLATOR 10-75 MC

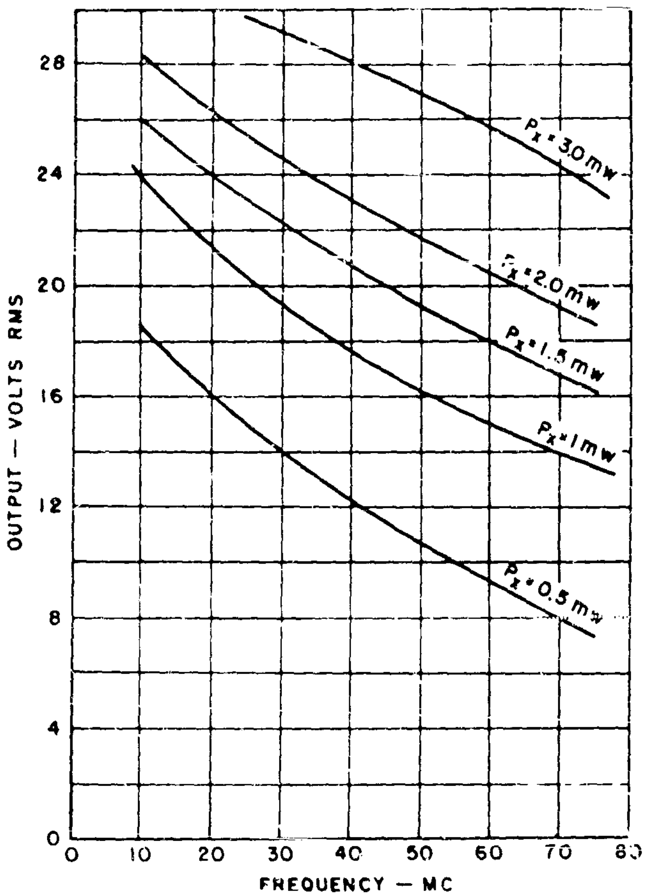


FIG. 7 — OUTPUT, CONSTANT P_x CURVES FOR THE GROUNDED GRID OSCILLATOR 10 - 75 MC

It is possible to operate the circuit over a band of frequencies without retuning the cathode coil. If the frequency of operation is within ±20 percent of the fixed-tuned frequency of the cathode coil, the output will vary less than 15 percent and the frequency correlation figure will be within 15 ppm from the cathode coil center frequency values. Crystal voltage correlation cannot be obtained since the crystal is not operated at the series resonant frequency. As a result, power dissipation figures are not easily determined, but lie in the range of values indicated in Fig. 5.

In order to utilise these curves for design of the Grounded Grid oscillator in the desired frequency range, examples are shown below.

e. Circuit Design Examples and Use of Curves

The circuit as shown in Fig. 1 has been found to provide the most satisfactory performance throughout the frequency range and is recommended for the majority of applications. In fact this circuit should be used without modification wherever possible. In some equipment designs the available supply voltage may not allow this circuit to operate to its full capability. In such cases design changes may be accomplished as shown in the later examples. Performance graphs for the recommended circuit are accurate to within ten percent. The design graphs yield prediction accuracies of output, with changes in any one component, in the order of 10 to 15 percent. For simultaneous changes in R_L, R_g, and R_k, the average of tested cases has resulted in accuracies of 20 to 25 percent. More than two-thirds of these cases showed accuracies better than this figure. Crystal drive voltage measurements, made with the assumption of resistive operation of the crystal, revealed prediction accuracies in the order of 25 to 30 percent.

It is recommended that wherever feasible the output coupling be adjusted to provide an effective load resistance of 5000 ohms to the oscillator at the frequency of operation. When this is not done reference must be made to the normalised load resistance graph of Fig. 25. Figure 28, which shows the effects on performance of variations in crystal resistance values, can be used to indicate the performance when a crystal of specific resistance is used or to show the range of performance of typical crystals for the Grounded Grid circuit at 10 to 75 mc. Performance is referenced to a crystal resistance of 25 ohms. Recommended military crystal types which can be used in this application are CR-19/U, CR-24/U, CR-28/U, CR-32/U, CR-35/U, CR-52/U, CR-54/U, CR-55/U, and CR-56/U. Reference should be made to "MIL-C-3098B Crystal Units, Quartz" for specific crystal information such as maximum resistance limits, physical configuration, and frequency range.

One of the chief values of the design method presented here is in the prediction of oscillator performance of a given design. At specified frequency and plate supply voltage values, performance of the recommended circuit is determined from Figs. 4 and 5. If the output and drive level values are other than those desired, reference is made to Figs. 6 and 7 and/or the normalised curves to determine which circuit parameter may be changed to produce the necessary results. Any parameter that must remain fixed would eliminate the use of its corresponding performance curve.

The normalised circuit component or performance factors are obtained by dividing the desired or necessary parameter value by the recommended circuit value and the result applied to the appropriate curves. For example, the reference load resistance is 5000 ohms, and if the desired load is to be 4500 ohms, the normalised load factor, K'_{RL}, is then 4500/5000, or 0.9. Similarly, if the reference circuit output voltage is known, or found, to be 8.4 volts, and an output of 13.0 volts is desired, then the normalized output factor N', is $\frac{13.0}{8.4}$, or 1.55. Normalized component factors are identified by the subscript, on N', which indicates the component being used, such as N'_{RL}, N'_{Rg}, etc., the normalized factors with changes in R_L, R_g, etc. Normalized performance factors, N', for output voltage, output power, and/or crystal drive have no subscripts. However, these factors are individually identified, to avoid confusion, by the statement, "N' for output voltage," etc., as used throughout the following text. Recommended circuit component or parameter values given in this manual should be followed, wherever possible, since the recommended circuit is optimum for typical application.

To illustrate the use of the design graphs, the following example is given:

Assume an oscillator is to be designed having the following circuit and performance requirements:

f_n = 60 mc

B+ = 100 volts

R_L = 4000 ohms

P_x = 2.0 mw (determined from MIL-C-3098B for particular crystal type)

Referring to Fig. 4, it can be seen that at a frequency of 60 mc and a B+ of 100 volts, the recommended circuit has an output of approximately 17.5 volts rms. The crystal drive, determined from Fig. 5, is 1.4 mw. At the required load of 4000 ohms, reference to Fig. 25 shows that for N'_{RL} = 4000/5000 = 0.8, the normalized output and crystal drive factors, N', are 0.87, each, where 5000 ohms is the reference circuit load resistance. This means that at the required load, the output will be 17.5 x 0.87 = 15.2 volts and the drive will be 1.4 x 0.87 = 1.2 mw. Since the nominal allowable drive is 2.0 mw, it may be desirable to investigate methods of increasing available output and taking advantage of the drive limit. This may be done in several ways. Three methods will be shown here.

The first method depends on the variability of the B+. If the plate supply voltage can be changed, then Figs. 6, 7 and 25 will be used to determine performance. For a drive of 2.0 mw, it can be seen from Fig. 6, that the B+ must be 115 volts for a 60 mc oscillator. From Fig. 7, it is determined that the output voltage is 20.5 volts for this level of drive. This is for the reference circuit. In order to account for the lower load of 4000 ohms, $N'_{RL} = 0.8$, and $N' = 0.87$, as shown in the original example. Since operation at 4000 ohms load reduces the drive by 0.87, a B+ value must be chosen which would drive the reference circuit at 2.0/0.87 = 2.30 mw. This occurs at B+ = 123 volts, approximately. Under these conditions, the output is 22.5 volts. However, the output at a load of 4000 ohms would be 22.5 x 0.87 = 19.6 volts.

For the second method, consider Fig. 26, which shows the normalized performance variations with changes in R_g. As the value of the grid bias resistor is made smaller both P_x and e_o increase. Since, at the required value of load P_x = 1.2 mw as determined above, it is desirable to lower the value of R_g to increase the drive to 2.0 mw. The factor, N', is then 2.0/1.2 = 1.66, for P_x. Then, $N'_{R_g} = 0.5$, for which, N' for e_o is 1.07. This means that a grid bias resistor of 10,000 ohms (reference circuit value) times N'_{R_g} (=0.5), or 5000 ohms, is the necessary value, and the drive will be 2.0 mw, at an output of 15.2 x 1.07 = 16.3 volts.

The third method uses the information found in Fig. 27, which shows the normalized variation of performance with changes in R_k, the cathode bias resistor. The drive is multiplied by the factor $N' = 1.66$ at $N'_{R_k} = 0.5$ of the reference circuit value, or 100 ohms. The output increases to 1.1 times the reference circuit value, or 16.7 volts, which is slightly more than that obtained by changing R_g.

The largest output in this case is obtained by changing B+ to obtain the 2.0 ma drive level. This will be true in most cases. Similar methods may be applied in those cases where fixed output voltage or power is required.

The two remaining graphs of Figs. 28 and 29 show performance variations with crystal resistance and tube transconductance. However, little control can be held over these parameters unless lengthy, selective tests are made. Nevertheless, the graphs are included to indicate their effect on circuit performance. It can be seen that a 100 percent increase in crystal resistance increases the drive and lowers the output voltage by only eight percent each. For a ten percent decrease in g_m, the output voltage decreases to nearly one-half and the drive to about three-fourths the original values. The graph indicates performance when using a type 5670 tube. The use of different tube types having approximately the same range of g_m values can be evaluated by this graph also, but might necessitate an adjustment in estimates of circuit stray capacitance and other operating characteristics.

f. Additional Performance Characteristics

Several additional oscillator performance characteristics have been determined and are presented here. The first of these is the stability characteristics of the Grounded Grid oscillator in the frequency range of 10 to 75 mc. Table II shows the figures for stability with changes in B+ and filament voltage. The correlation figure is also given for a range of crystal resistance and B+ values. Three crystals operating at each of three frequencies,

10 mc					30 mc					75 mc				
R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f
23	75	- 6.5	-	-	18	75	- 6.9	-	-	22	75	-15.3	-	-
	100	- 6.2	0.2	-		100	- 4.1	0.5	-		100	-12.1	2.2	-
	125	- 6.0	-	-		125	- 0.9	-	-		125	- 9.6	-	-
	150	- 5.3	0.4	-		150	+ 0.6	0.9	-		150	- 0.9	1.9	-
28	75	- 0.9	-	-	26	75	- 0.6	-	-	40	75	-10.9	-	-
	100	- 1.5	0.1	0.1		100	+ 1.9	0.6	-		100	- 7.7	2.1	-
	125	- 1.9	-	-		125	+ 4.6	-	-		125	- 4.5	-	-
	150	- 2.3	0.1	-		150	+ 6.7	1.1	-		150	- 1.2	4.4	-
33	75	+ 7.8	-	-	58	75	+ 1.3	-	-	51	75	- 0.1	-	-
	100	+ 8.2	0.1	-		100	+ 5.1	0.8	0.4		100	+ 1.9	0.7	0.6
	125	+ 7.3	-	-		125	+ 6.9	-	-		125	+ 3.5	-	-
	150	+ 6.3	0.4	-		150	+ 8.1	0.8	-		150	+ 5.2	1.3	-

R_x in ohms, B+ in volts and Stability figures in parts per million

TABLE II - STABILITY CHARACTERISTICS OF THE GROUNDED GRID OSCILLATOR

10 - 75 mc

10, 30, and 75 mc, are shown. Δf_s is the correlation figure, and is defined as the difference between the oscillator operating frequency and the series resonant frequency of the crystal as determined by measurement in the TS-683/TSM CI meter at 2.0 mw drive. This figure is given in parts per million (ppm) of the nominal crystal frequency. In the 10 to 40 mc range, L_{sf} is required to maintain acceptable correlation figures. Δf_b is defined as the difference between the oscillator operating frequency and the frequency obtained when the plate supply voltage is varied ±10 percent from a fixed value. Since the difference between the frequency readings at +10 and -10 percent is generally less than 0.1 ppm, only one value is given. This figure is also expressed in ppm of the nominal crystal frequency. Δf_f is similar to Δf_b, where the filament voltage is varied ±10 percent.

An important performance characteristic is that of frequency variation with temperature. Crystal unit specifications for this frequency range, call for a maximum deviation from the nominal frequency of 50 ppm throughout the temperature range of -55°C to +90°C. However, typical changes from the mean frequency values encountered for these units are between 15 to 25 ppm. Temperature coefficients of circuit component parts will cause the operating frequency to deviate further. Circuit temperature-frequency variations are less than 25 ppm and together with the maximum crystal unit deviation, amounts to less than 75 ppm. Inclusion of variations due to ten percent B+ and filament voltage changes raises this figure to a maximum of 85 ppm. However, use of typical crystals yields a value of less than 60 ppm. Of course, the total frequency deviation may be substantially reduced by use of crystal ovens, (which decrease crystal frequency deviations from a maximum value of 50 ppm to approximately 10 ppm), temperature-compensated components and temperature stabilizing circuit enclosures. Curves of frequency-temperature variations are found in Figs. 20 through 24, for both the Grounded Grid and Cathode Coupled oscillators operating at frequencies of 10, 30, 75, 105, 135, and 150 mc. The graphs show the variations in frequency of the crystal alone and for each circuit. Typical variations are shown for two crystals at each of the frequencies in the range 75 to 150 mc.

A third performance characteristic is that of harmonic content in the output of the oscillator circuits. Comments on this characteristic are found in the final paragraph of Part A.2.f., and details are found in Tables VI through VIII.

It may be desirable, in some cases, to utilize the circuit with an untuned cathode. Although the use of a tuned cathode coil provides higher oscillator output voltages, the advantages of the untuned case are the elimination of the part itself, a simpler tuning procedure, and broad band, rather than fixed, frequency operation. Information on the Grounded Grid oscillator operating with an untuned cathode circuit is therefore presented. In general, some component changes are necessary in the reference circuit. Typical values for the ranges 10 to 20 and 20 to 40 mc are listed below, where resistance is in ohms and capacitance is in mmfd. All other components remain the same as in the reference circuit. It should be noted that for this application, L_{sf} is not used.

	Frequency Ranges	
Component	10 to 20 mc	20 to 40 mc
R_k	330	330
C_f	470	40

Operation beyond 40 mc is very poor and it is not advisable to eliminate the cathode coil in that frequency range.

Performance curves for this application of the Grounded Grid oscillator are shown in Fig. 8. Although frequency correlation is reasonable, provided the component values suggested above are used, stability is poor and becomes worse with increasing frequency of operation.

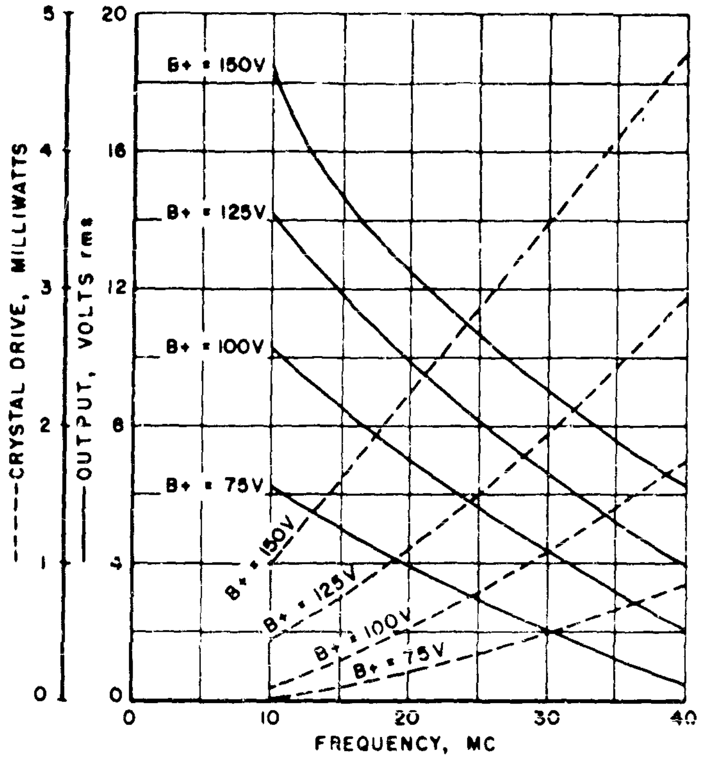


FIG. 8 — PERFORMANCE OF THE GROUNDED GRID OSCILLATOR WITH UNTUNED CATHODE CIRCUIT

10 - 40 MC

2. THE GROUNDED GRID OSCILLATOR - 75-150 MC

a. Circuit Description

The circuit diagram of the Grounded Grid oscillator recommended for use in the 75 to 150 mc frequency range is shown in Fig. 9. Coil winding data is presented in Table III and Fig. 10.

The oscillator circuit has the component and circuit parameter values given in Part A.1.a., except for the reference value of R_x which is 51 ohms for this frequency range.

b. Component and Circuit Construction Details

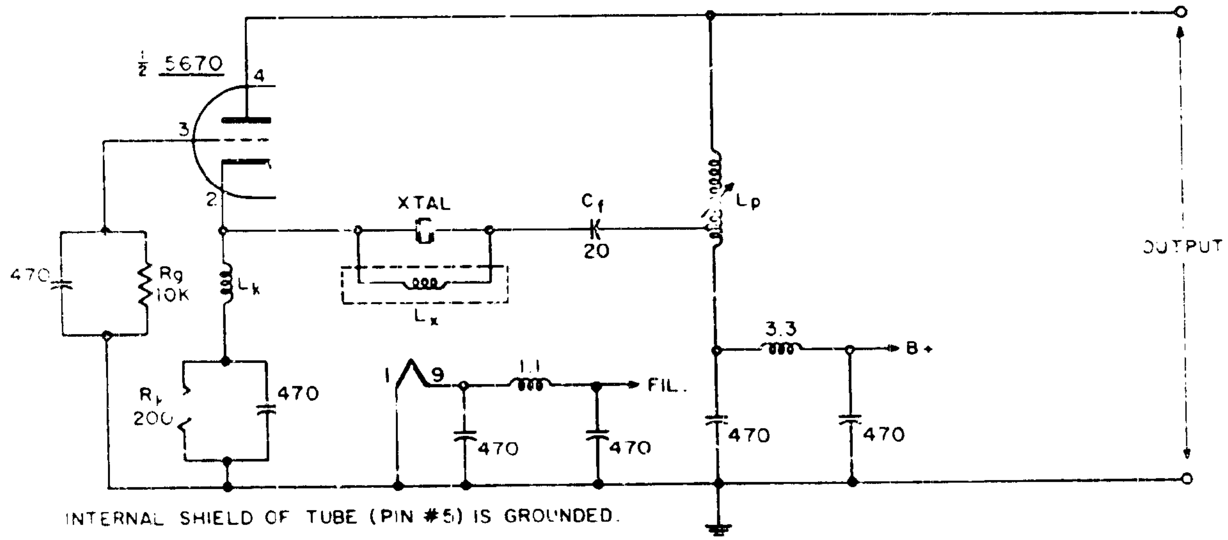
In general, the discussion of components and circuit details given in Part A.1.b. applies here. However, greater care must be given to lead dress, grounding, and parts placement at these higher frequencies.

c. Circuit Tuning Procedure

See Part A.1.c.

d. Circuit Performance Characteristics

Curves of output voltage and power, and crystal drive versus frequency of operation, are shown in Figs. 11 and 12, respectively. In addition, curves of required values of B+ and the resultant output for constant values of crystal drive over the frequency range are presented in Figs. 13 and 14, respectively. The graphs depict performance of a circuit having component values indicated in Fig. 9. The performance figures obtained from changes in component value are normalized with respect to the recommended circuit figures. The resulting normalized graphs are common to the entire 10 to 150 mc frequency range and are shown in Figs. 25 through 29, on fold-out pages 55 through 59. These graphs show output voltage, output power, and crystal drive level as a function of the values of R_L, r_g, R_k, R_x, and g_m, respectively.



INTERNAL SHIELD OF TUBE (PIN #5) IS GROUNDED.

R IN OHMS
C IN $\mu\mu f$
L IN μh
UNLESS OTHERWISE SPECIFIED

SEE TABLE III AND FIG. 10
FOR VALUES OF L_k, L_p, AND L_x

FIG. 9 — GROUNDED GRID OSCILLATOR
75 - 150 MC

Freq.	Coil	Coil Form	Wire Size	Coil Length	Turns	Tap	L	Q	L_m	k	L_1
mc	-	-	gage	inches	-	turns	µh	-	µh	-	µh
	L_x	-	32	1/4	21	-	.67	10	-	-	-
75	L_k	LS6-0	24	1/2	8	-	.39	135	-	-	-
	L_p	LS6-0	20	5/8	8	1.5	.42	110	.04	.53	.03
	L_x	-	27	1/4	16	-	.48	5	-	-	-
105	L_k	LS6-0	20	1/2	6	-	.19	133	-	-	-
	L_p	LS6-0	20	1/2	6	1.0	.20	85	.04	.51	.03
	L_x	-	24	3/8	10	-	.23	25	-	-	-
135	L_k	LS6-D	20	3/8	4	-	.11	75	-	-	-
	L_p	LS6-0	20	1/2	3.5	0.5	.12	85	.03	.42	.03
	L_x	-	24	5/32	8	-	.18	33	-	-	-
150	L_k	LS6-D	20	9/16	4	-	.09	105	-	-	-
	L_p	LS6-0	20	1/2	3	1.0	.09	85	.03	.52	.02

<u>NOTE</u>: L_x is wound on a 2K, 1/2 watt carbon composition resistor. The indicated coil types for L_k and L_p are Cambridge Thermionic Corp. forms, 0.26" O.D., 27/32" long. LS6- is the part number specifying the coil form type and size. The suffix designates the core formulation.

The tap on L_p is measured from the ground end of the coil.

The inductance and Q of all crystal coils, L_x, were measured at 50 mc on a Boonton Radio Corp. Q Meter, Model 160A. The inductance and Q of L_k and L_p were measured at their operating frequencies on a Boonton Radio Corp. Q Meter, Model 170A.

TABLE III - GROUNDED GRID OSCILLATOR COIL DATA

75 - 150 mc

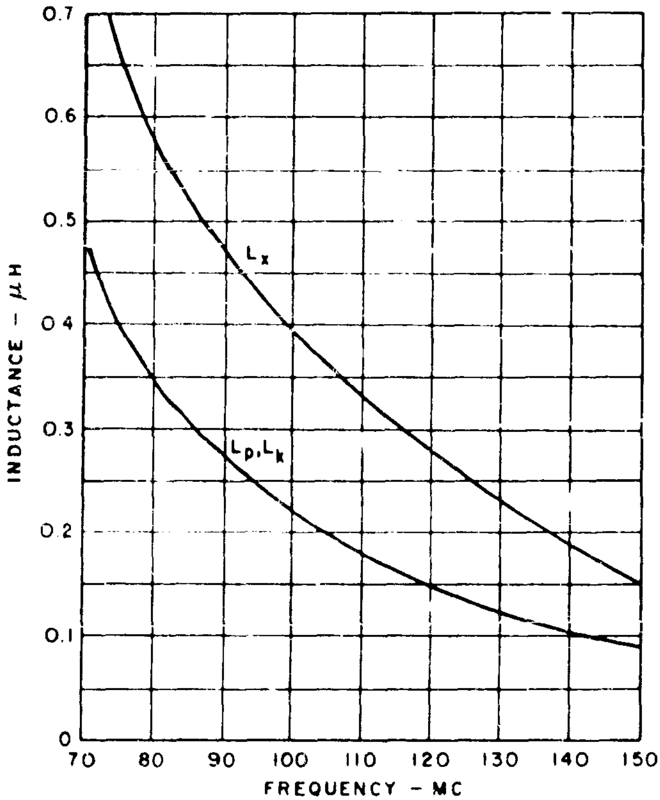


FIG. 10 —INDUCTANCE VS FREQUENCY FOR THE GROUNDED GRID OSCILLATOR COILS 75 - 150 MC

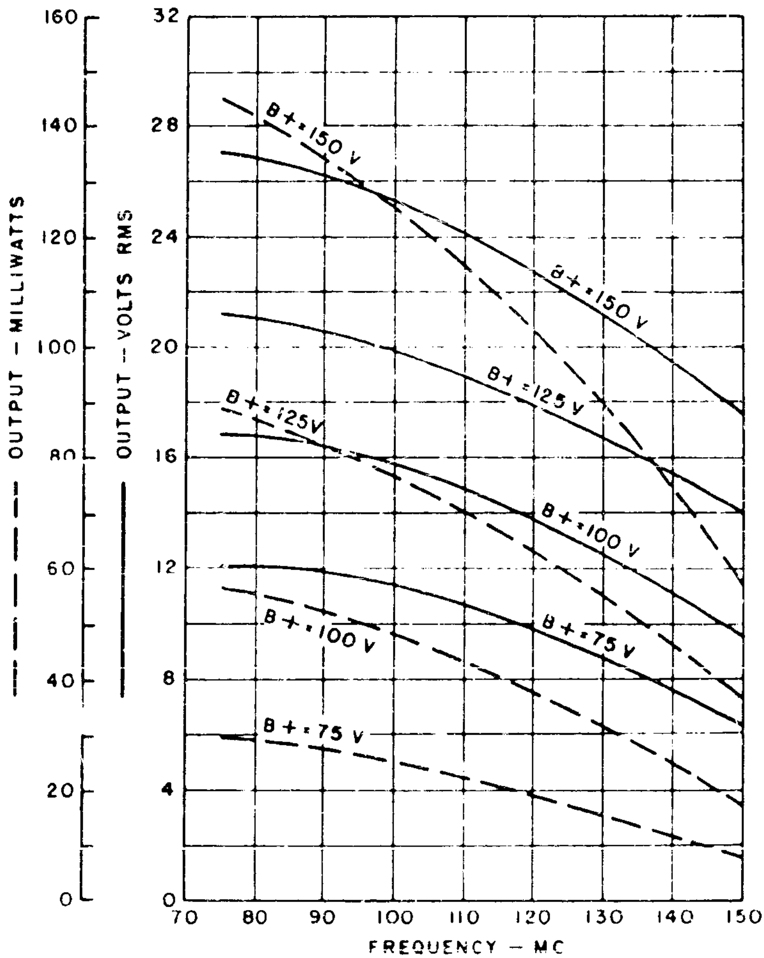


FIG. 11 —— OUTPUT VOLTAGE AND POWER VS FREQUENCY FOR THE GROUNDED GRID OSCILLATOR 75 - 150 MC

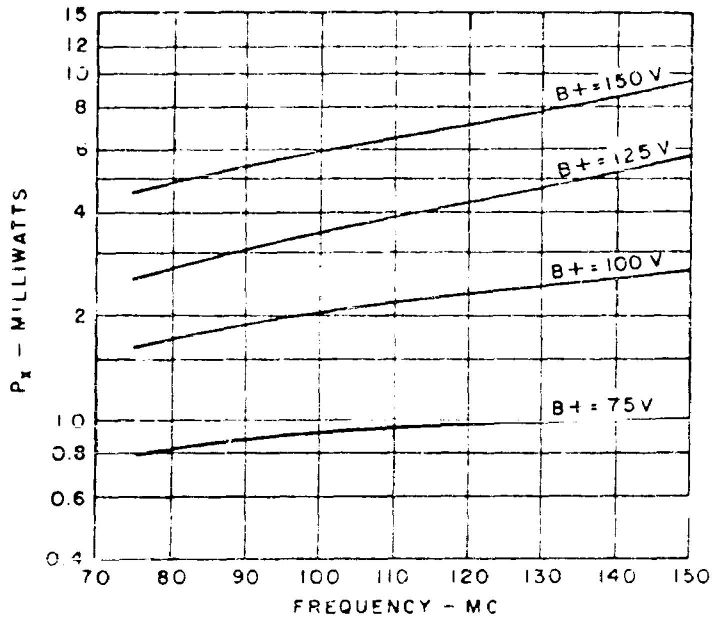


FIG 12 —— CRYSTAL DRIVE VS. FREQUENCY FOR THE GROUNDED GRID OSCILLATOR 75 - 150 MC

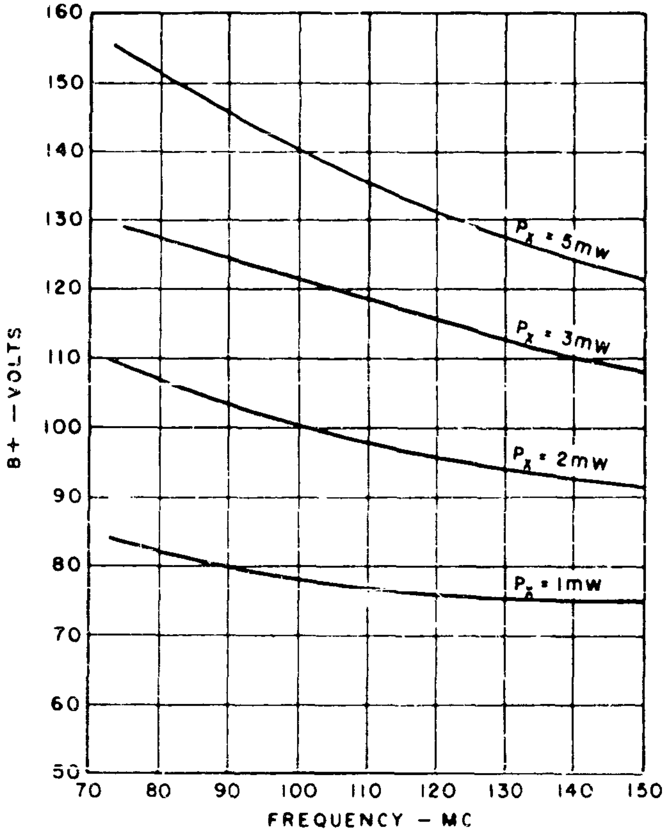


FIG 13 B+, CONSTANT P_x CURVES FOR THE GROUNDED GRID OSCILLATOR 75-150 MC

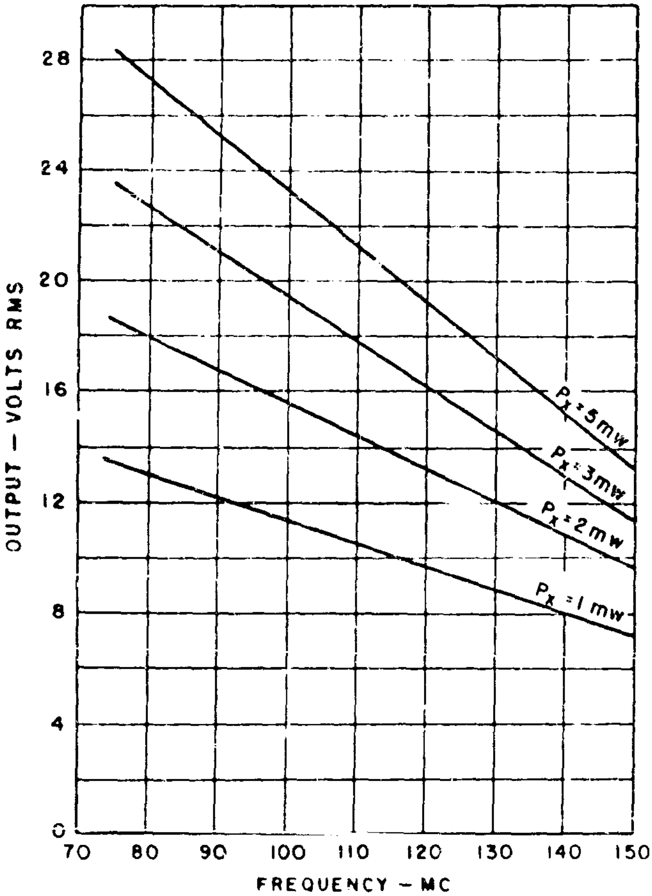


FIG. 14 — OUTPUT, CONSTANT P_x CURVES FOR THE GROUNDED GRID OSCILLATOR 75-150 MC

Figure 15 combines the effect on output of increasing or decreasing R_L, R_g, and R_k simultaneously and by the same percentage. This figure is obtained by taking the product of the average output factors, represented by the curves in Figs. 25, 26, and 27, resulting from the same percentage of resistance change for each of R_L, R_g, and R_k.

The graph affords a check on the reliability of the design data for a wide range of operating conditions. If, for example, these three components are each increased by a factor of 2.0 over the reference value, it can be seen from the graph that the output decreases to 95 percent of the reference output.

Results of circuit measurements to check this are shown in Table IV. Here, two resistance factor values, 0.65 and 1.66, were used. This means that R_L, R_g, and R_k values in the new circuit are the stated percentages of the reference circuit values. From Fig. 15, the corresponding output factors, N', are 0.85 and 0.98, respectively. A circuit was constructed whose components corresponded to these values and output was measured at four levels of supply voltage. These output measurements are tabulated in the column headed "e_o". The theoretical changes are listed under the column headed "$N'e_o'$" where e_o' is the reference circuit output and N' is the output factor resulting from the use of the information in Fig. 15.

The effect on output voltage resulting from the use of different tube types and having a range of values of g_m is shown in Figs. 16 through 19, inclusive, where the frequencies of operation were 75, 105, 135, and 150, respectively. Each graph represents the output obtained from the reference circuit using a 6AJ4, a 6AB4 miniature triode, and a single section of a

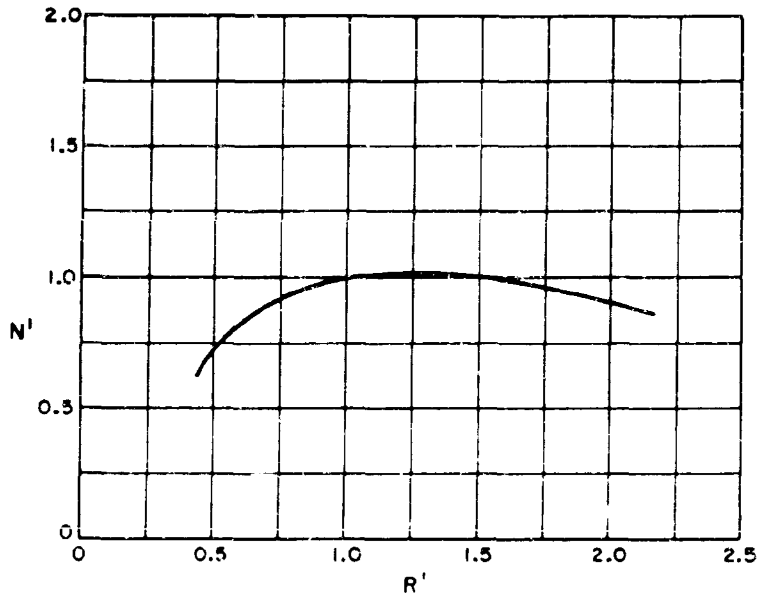


FIG. 15—NORMALIZED CURVE FOR COMBINED CHANGE IN GRID, CATHODE AND LOAD RESISTANCES FOR GROUNDED GRID OSCILLATORS.

Circuit Conditions			75 mc		105 mc		135 mc		150 mc	
R'	N'	B+	e_o	$N'e_o'$	e_o	$N'e_o'$	e_o	$N'e_o'$	e_o	$N'e_o'$
0.65	0.85	50	2.6	3.6	3.3	2.0	-	-	3.0	3.6
		75	6.5	10.2	6.7	9.4	-	-	5.6	5.3
		100	9.9	14.3	9.8	13.2	6.8	10.2	8.4	8.2
		125	13.8	17.9	13.1	16.5	10.7	13.6	11.6	11.9
1.66	0.98	50	5.0	4.1	6.3	5.3	-	-	3.4	3.9
		75	10.7	11.8	11.2	10.8	7.2	7.8	6.5	6.1
		100	15.8	16.5	16.0	15.0	11.5	11.6	9.7	9.5
		125	20.3	20.6	21.0	19.1	15.4	15.6	13.3	13.7

TABLE IV - COMPARISON OF PREDICTED AND MEASURED PERFORMANCE OF THE GROUNDED GRID OSCILLATOR CIRCUIT

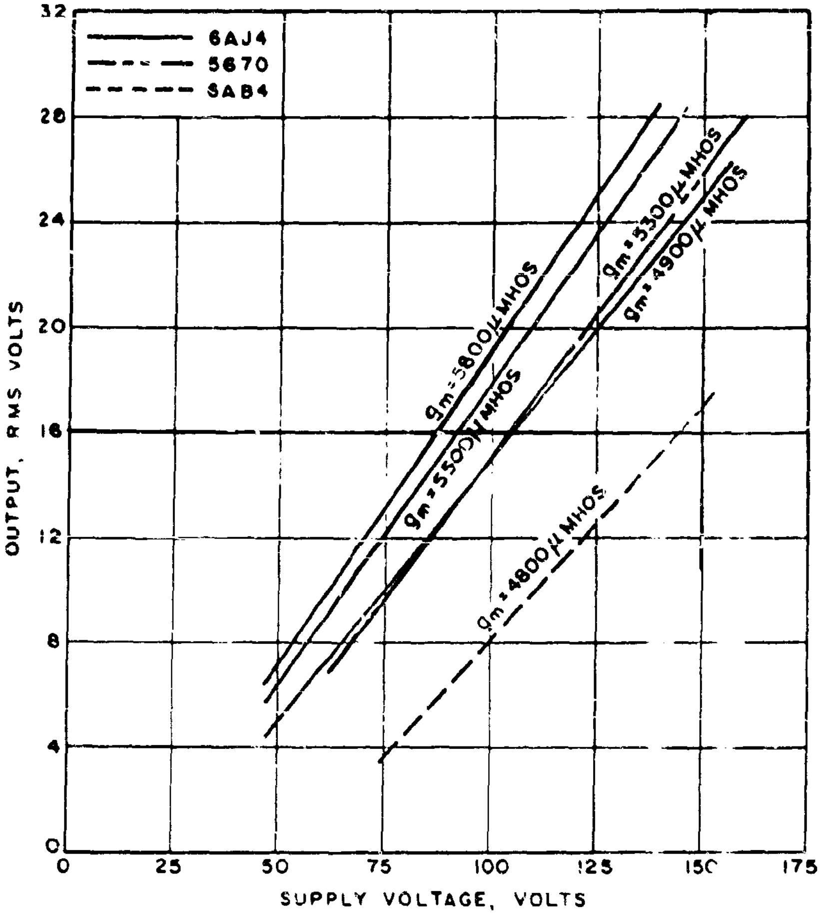


FIG. 16——OUTPUT, g_m CHARACTERISTICS FOR THE GROUNDED GRID REFERENCE OSCILLATOR AT 75 MC.

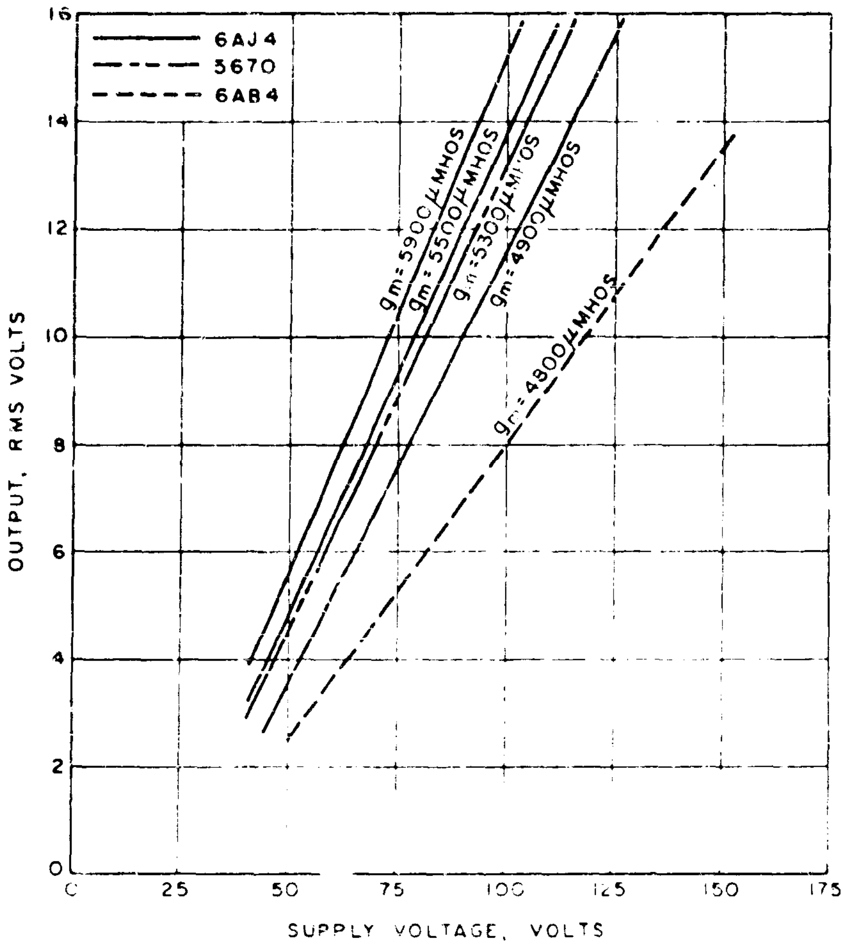


FIG. 17—OUTPUT, g_m CHARACTERISTICS FOR THE GROUNDED GRID REFERENCE OSCILLATOR AT 105 MC.

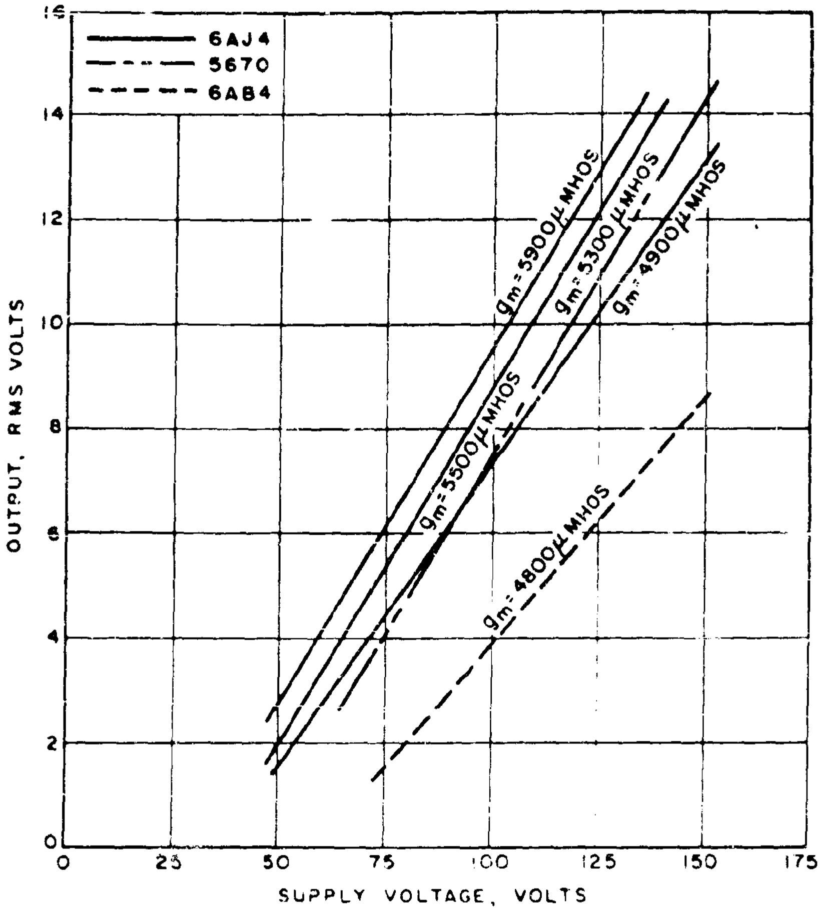


FIG. 18 —— OUTPUT, g_m CHARACTERISTICS FOR THE GROUNDED GRID REFERENCE OSCILLATOR AT 135 MC.

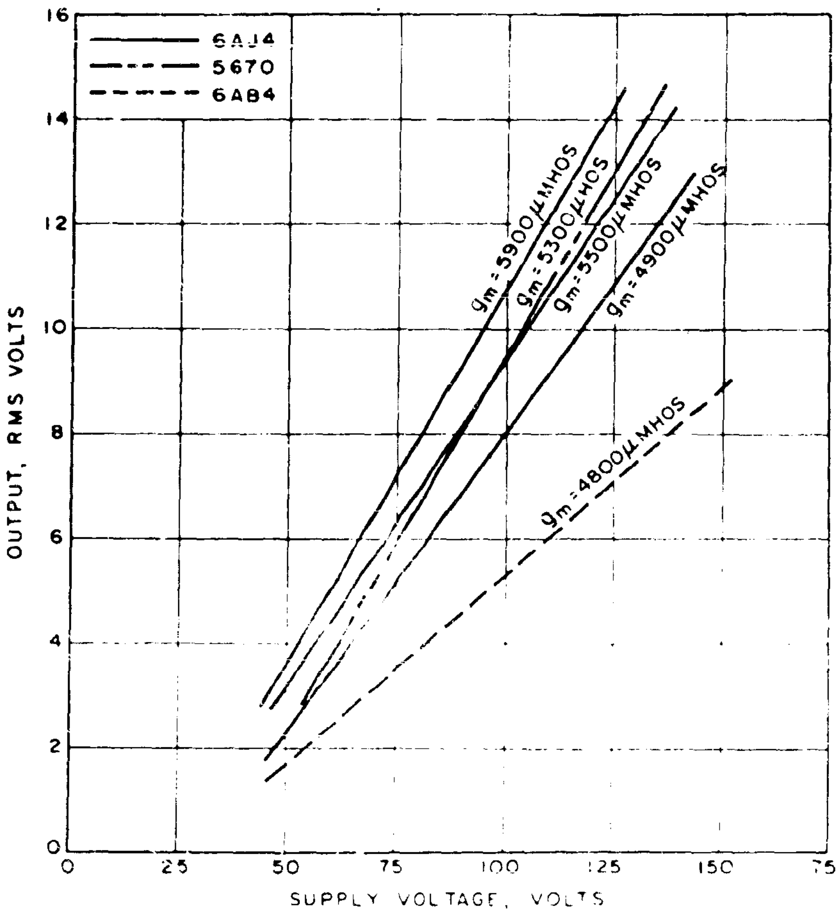


FIG. 19—OUTPUT, g_m CHARACTERISTICS FOR THE GROUNDED GRID REFERENCE OSCILLATOR AT 150 MC

5670 miniature dual triode. Three 6AJ4 tubes, having different values of g_m, were used. The reference circuit component tube is a 5670 having a measured g_m of 5300 micromhos. All values of g_m were determined with a Hickok Model 533 Mutual Transconductance Tester under standard test conditions.

By comparing the range of output voltages available at various levels of B+ for the different values of tube transconductance, it was determined that this information could be normalized in the form of output voltage versus g_m. This is the basis of the curve of Fig. 29.

In addition to the information discussed above, a new ceramic planar triode, the 6BY4, was tested in a Grounded Grid oscillator circuit configuration. Output and drive level data compared with that obtained using conventional tubes. However, the manufacturer's tube transconductance specifications could not be met with the units made available to the program. Values for g_m were somewhat less than 5000 micromhos.

In order to utilize these curves for the design of the Grounded Grid oscillator in the desired frequency range, examples are shown below.

e. Circuit Design Examples and Use of Curves

The circuit as shown in Fig. 9 has been found to provide the most satisfactory performance throughout the frequency range and is recommended for the majority of applications. This circuit should be used without modification wherever possible. For special performance requirements, where the recommended circuit does not give the desired results, circuit design changes may be accomplished, as will be shown in the design examples.

Recommended military crystal types that may be used in this application are CR-54/U and CR-56/U. The specifications on these units cover frequencies up to and including 87 mc. Maximum crystal resistances used at

75 and 105 mc were 60 ohms. Maximum resistance used at 135 mc, and 150 mc was 100 ohms.

Although MIL-3098B does not cover crystals operating above 87 mc, available units and SCEL recommendations indicate a maximum crystal resistance of 60 ohms up to an including 125 mc and a maximum of 100 ohms to 150 mc. Although good quality units were available for the present investigations up to 150 mc, one unit which has a series resonant resistance of 160 ohms was included in the data.

Of the crystals available, the spread in crystal resistance at certain frequencies is limited. In order to expand the range, resistors were used in the circuit as substitution elements and performance measurements were made. Where resistors were used in place of existing crystals, no appreciable change in voltage was noted, provided proper reactive compensation of the resistors was made. In this manner, the reference circuit crystal resistance of 51 ohms was made available throughout the frequency range, although there were no crystal units with this value of R_x at all frequencies.

To illustrate the use of the design graphs, the following example is given using the format of Part A.1.e.

Assume an oscillator is to be designed having the following circuit and performance requirements.

$$f_n = 105 \text{ mc}$$

$$B+ = 100 \text{ volts}$$

$$R_L = 4000 \text{ ohms}$$

$$P_x = 2.0 \text{ mw}$$

The 2.0 mw drive level figure is determined from general MilSpecs for crystals in this frequency range, or from consideration of frequency stability for those units not given in MIL-C-3098B. The greater the drive, the more the frequency stability may be degraded.

Reference to Fig. 11 shows that at a frequency of 105 mc and a B+ of 100 volts, the output is approximately 15.3 volts rms for the recommended circuit. The crystal drive, from Fig. 12, is found to be 2.1 mw. At the required load of 4000 ohms, reference to Fig. 25 shows that for N'_{R_L} = 4000/5000 = 0.8, the normalized output and crystal drive factors, N', are 0.87 each, where 5000 ohms is the reference circuit load resistance. This means that at the required load, the output will be 15.3 x 0.87 = 13.3 volts and the drive will be 2.1 x 0.87 = 1.8 mw. Since the nominal allowable crystal drive is 2.0 mw, it may be desirable to investigate methods of increasing available output and take advantage of the drive limit. This may be done in several ways. Three methods will be shown here.

One method depends on the variability of B+. If the plate supply voltage can be changed, then Figs. 13 and 14 will be used to determine performance. For a drive of 2.0 mw, it can be seen, from Fig. 13, that the B+ must be 99 volts at 105 mc. From Fig. 14, it is determined that the output voltage is 15.0 volts for this level of drive. However, this is for the reference circuit. In order to account for the lower load of 4000 ohms, N'_{R_L} = 0.8 and N' = 0.87, as shown in the original example. Since operation at 4000 ohms load reduces the drive by 0.87, a B+ value must be chosen which would drive the reference circuit at 2.0/0.87 = 2.30 mw. This occurs at a B+ = 107 volts, approximately. Under these conditions, the output is 16.2 volts. However, the output at a load of 4000 ohms would be 16.2 x 0.87 = 14.1 volts.

The second method uses Fig. 26, which shows the normalized performance variations with changes in R_g. As the value of the grid bias resistor is made smaller, both P_x and e_o increase. Since, at the required value of load, P_x = 1.8 mw, as determined above, it is desirable to lower the value of R_g to increase the drive to 2.0 mw. The factor N', is then 2.0/1.8 = 1.11, for P_x. Then, N'_{R_g} = 0.85, for which N' for e_o is 1.03. This means that a grid bias resistor of 10,000 ohms (reference circuit value) times N'_{R_g} (=0.85), or 8500 ohms, is the necessary value, and the drive will be 2.0 mw, at an output of 13.3 x 1.03 = 13.7 volts.

A third method uses the information found in Fig. 27, which shows the normalized variation of performance with changes in R_k, the cathode bias resistor. To increase the drive by a factor of 1.11, the output increases by a factor of N' = 1.04 at N'_{R_k} = 0.90. Then the new value of R_k is 200 x 0.90 = 180 ohms with an output of 13.3 x 1.04 = 13.8 volts.

The largest output in this case is obtained by changing Be to obtain the 2.0 mw drive level. Similar methods may be applied where fixed values of output voltage or power are required. In the examples shown above it is questionable if the labor involved in modifying the circuit is justified to increase the output voltage. The reference circuit output of 13.3 volts using the required load is increased by the modifications to a maximum of 14.1 volts, an increase of only six percent. However, in those cases where the resultant drive is somewhat lower than 2.0 mw, i.e., in the order of 15 percent or more, modification of the circuit is advisable. Similarly, when the drive is excessive by about the same percentage, circuit changes should be effected to reduce this power dissipation.

The two remaining graphs of normalized performance curves (with respect to R_x and g_m) have been discussed in Part A.1.e., A.2.d. and in this section. Further, the generalized design method for circuit changes follows the pattern described in the same section noted above.

f. Additional Performance Characteristics

Additional performance characteristics for the Grounded Grid operating in the 75 to 150 mc frequency range have been determined and are presented here. Table V shows the figures for stability with changes in B+ and filament voltage. The correlation figures are also given for a range of crystal resistances and B+ values. Three crystals operating at each of four frequencies, 75, 105, 135, and 150 mc, are shown. The definitions of Δf_s, Δf_b, and Δf_f have been given in Part A.1.f.

A second performance characteristic is the change in frequency with variations in temperature (see Figs. 20 through 24). For this frequency range, complete specifications on the crystals are not available; however, for the -55°C to +90°C range, a maximum deviation of 50 ppm from the nominal frequency of the crystal is assumed. Typical values of deviation from the mean values encountered for these units are between 10 and 30 ppm. Temperature coefficients of circuit component parts will cause the operating frequency to deviate further. Circuit temperature-frequency variations are less than 30 ppm and when combined with the maximum crystal unit deviation totals less than 80 ppm for typical conditions. Inclusion of variations due to B+ and filament voltage changes of ten percent raises this figure to a maximum of 90 ppm. However, typical operation yields values less than 70 ppm.

A third performance characteristic is that of harmonic content in the output of the oscillator circuits. It has been found that harmonics are of rather low amplitude. However, practical application of these circuits to communications equipment would require additional filtering. Further, the harmonic content is not high enough for application to frequency synthesizing or frequency multiplying directly from the harmonics. Measurements show the

75 mc					105 mc					135 mc					150 mc				
R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f
23	75	-15.3	-	-	33	75	-12.2	-	-	51	75	- 4.1	-	-	53	75	- 6.2	-	-
	100	-12.1	2.2	-		100	- 2.3	3.0	-		100	- 0.7	2.4	0.5		100	+ 1.7	4.7	2.0
	125	- 9.6	-	-		125	+ 7.1	-	-		125	+ 5.4	-	-		125	+11.3	-	-
	150	- 0.9	1.9	-		150	+16.4	6.2	-		150	+ 8.9	5.1	-		150	+23.7	7.0	-
40	75	-10.9	-	-	40	75	- 5.9	-	-	68	75	-12.1	-	-	68	75	-11.0	-	-
	100	- 7.7	2.1	-		100	+ 5.6	3.4	-		100	- 2.6	5.9	-		100	- 1.9	4.4	-
	125	- 4.5	-	-		125	+13.2	-	-		125	+ 5.1	-	-		125	+ 8.4	-	-
	150	- 1.2	4.4	-		150	+23.0	8.0	-		150	+12.5	7.8	-		150	+16.6	6.9	-
51	75	- 0.1	-	-	46	75	- 6.9	-	-	80	75	- 2.5	-	-	91	75	-19.0	-	-
	100	+ 1.9	0.7	0.6		100	- 0.5	3.4	0.6		100	+ 1.7	5.4	-		100	- 8.3	7.2	-
	125	+ 3.5	-	-		125	+ 9.4	-	-		125	+ 4.9	-	-		125	- 0.8	-	-
	150	+ 5.2	1.3	-		150	+21.8	8.4	-		150	+11.4	6.0	-		150	+ 7.5	6.4	-

R_x in ohms, B+ in volts and Stability figures in parts per million

TABLE V - STABILITY CHARACTERISTICS OF THE GROUNDED GRID OSCILLATOR

75 - 150 mc

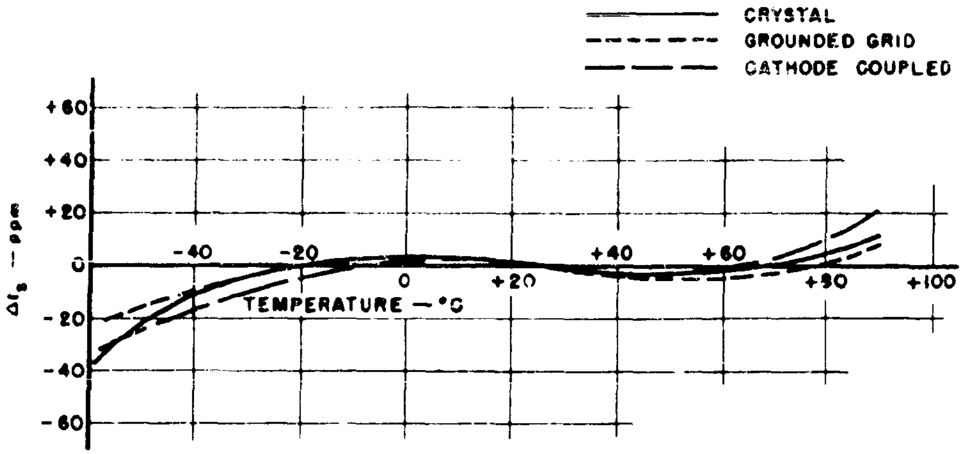


FIG. 20a — FREQUENCY TEMPERATURE CHARACTERISTICS
$R_x = 33\ \Omega$, $f = 10$ mc
CRYSTAL #495

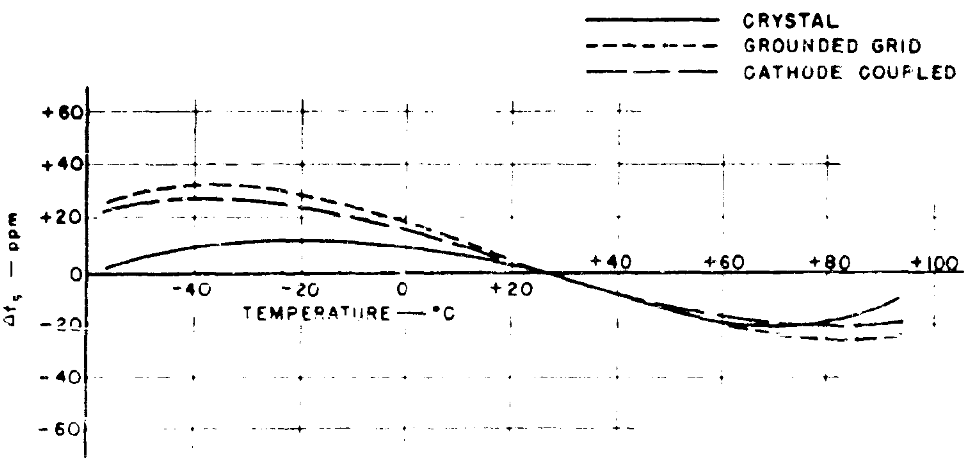


FIG. 20b — FREQUENCY TEMPERATURE CHARACTERISTICS
$R_x = 18\ \Omega$, $f = 30$ mc
CRYSTAL #459

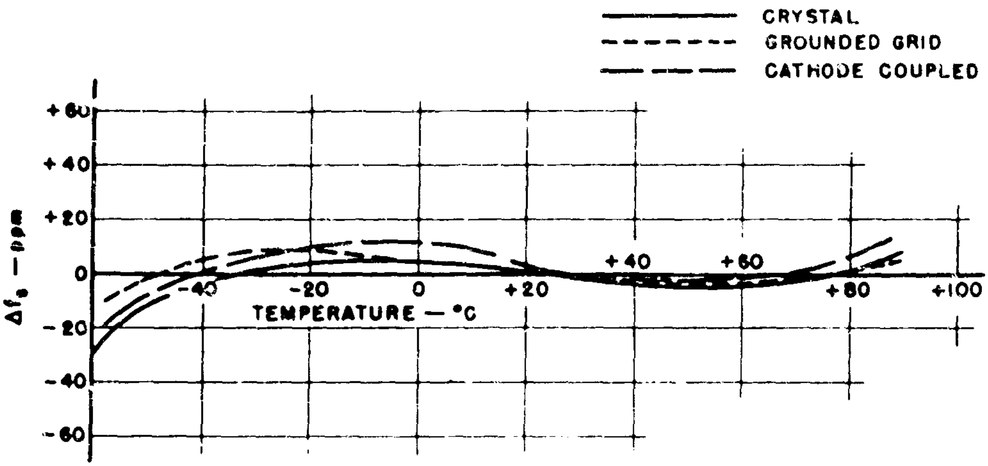


FIG. 21a —— FREQUENCY TEMPERATURE CHARACTERISTICS

$R_x = 40\,\Omega$, $f = 75$ mc

CRYSTAL #826

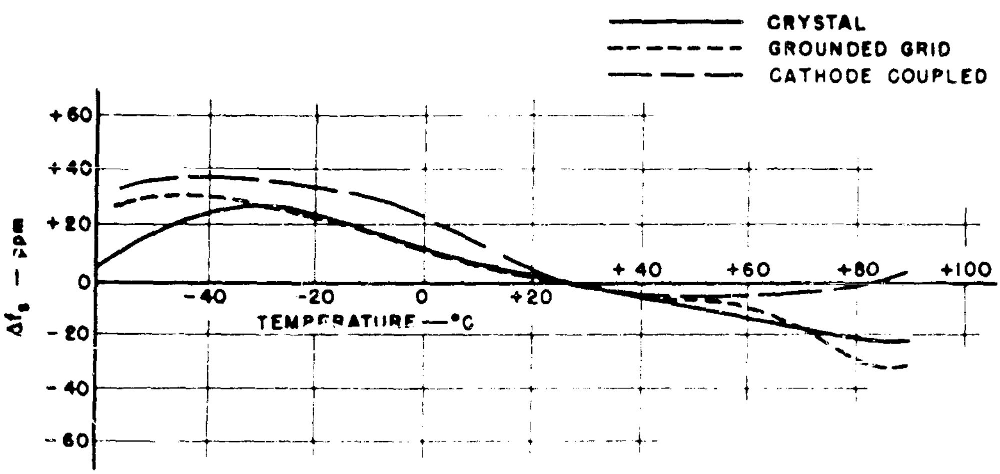


FIG. 21b —— FREQUENCY TEMPERATURE CHARACTERISTICS

$R_x = 51\,\Omega$, $f = 75$ mc

CRYSTAL #801

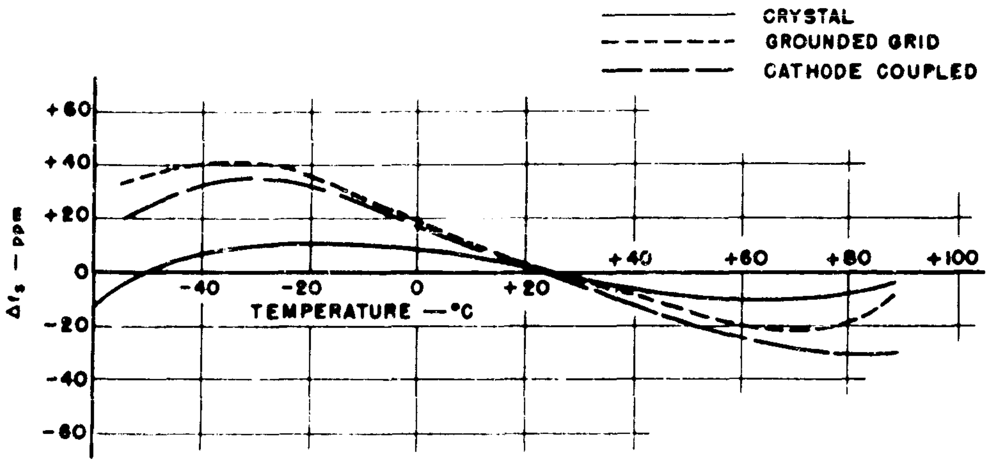


FIG. 22a — FREQUENCY TEMPERATURE CHARACTERISTICS

R_x = 46 Ω, f = 105 mc

CRYSTAL #849

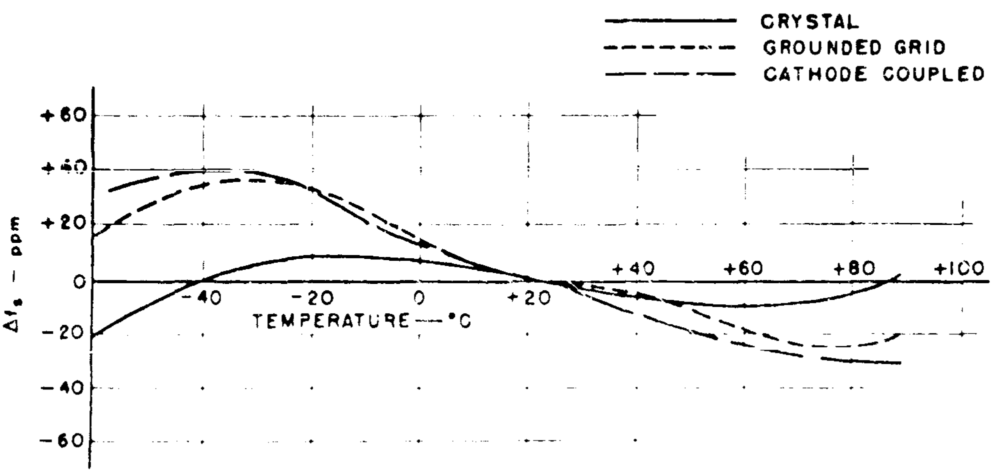


FIG. 22b — FREQUENCY TEMPERATURE CHARACTERISTICS

R_x = 51 Ω, f = 105 mc

CRYSTAL #826

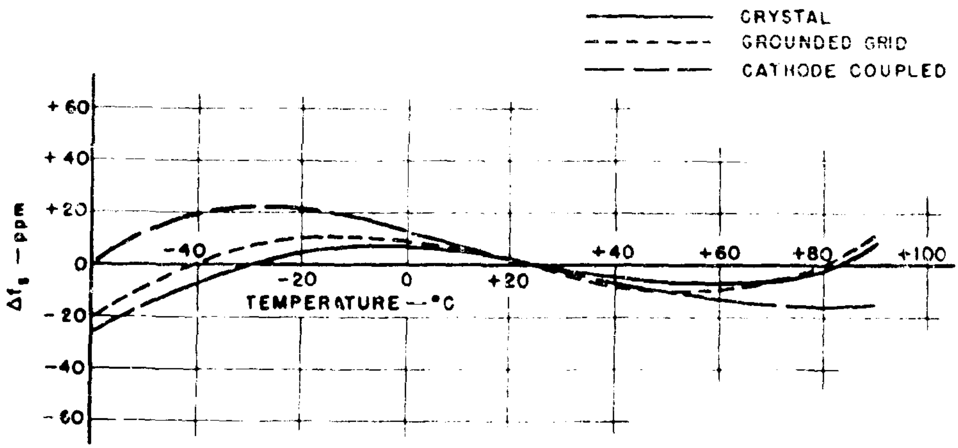


FIG. 23a — FREQUENCY TEMPERATURE CHARACTERISTICS
R_x = 51 Ω, f = 135 mc
CRYSTAL #833

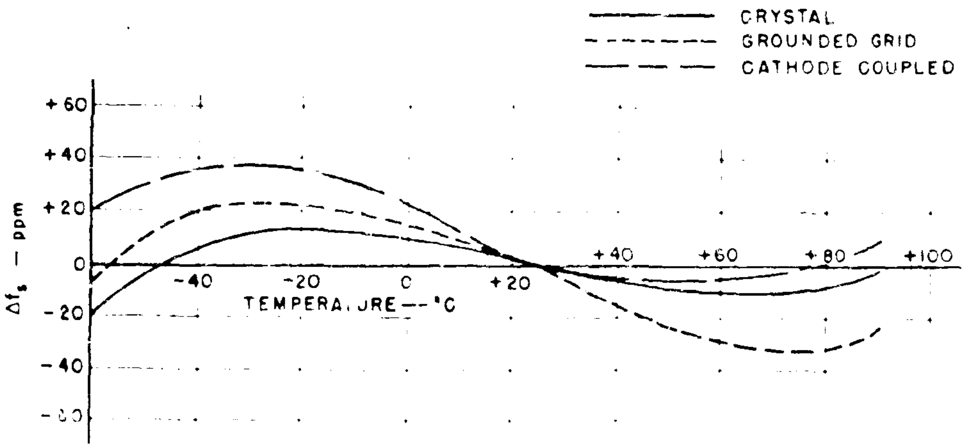


FIG. 23b — FREQUENCY TEMPERATURE CHARACTERISTICS
R_x = 80 Ω, f = 35 mc
CRYSTAL #870

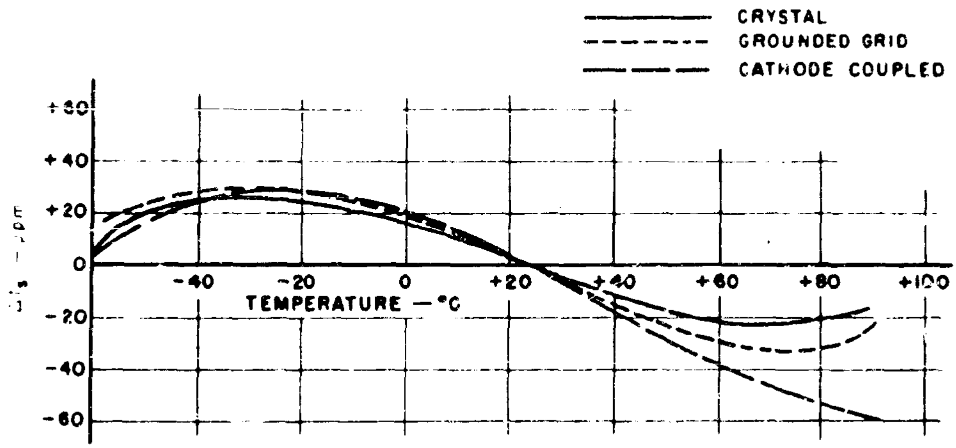


FIG. 24a — FREQUENCY TEMPERATURE CHARACTERISTICS
$R_x = 53\ \Omega$, $f = 150$ mc
CRYSTAL #843

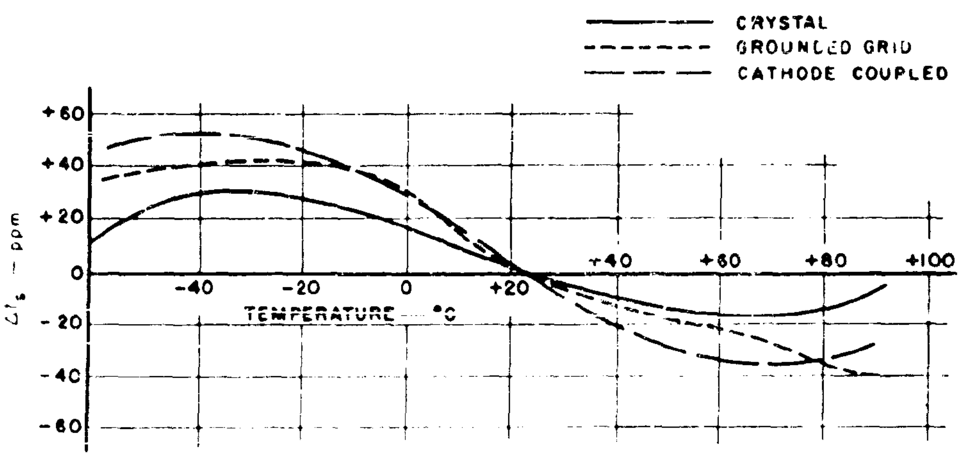


FIG. 24b — FREQUENCY TEMPERATURE CHARACTERISTICS
$R_x = 90\ \Omega$, $f = 150$ mc
CRYSTAL #864

second harmonic to be about 20 db below the fundamental and the sixth harmonic about 40 db below the fundamental for typical operating conditions. These measurements also indicate an increase in harmonic content with increases in circuit operating level (higher B+ level, greater crystal drive levels, etc.). Detailed information of the harmonic content of the Grounded Grid and Cathode Coupled oscillators are presented in Tables VI through VIII. Operation at two levels of B+ and with two values of crystal resistance are given.

75 mc

HARMONIC	50v	100v
2	21.1	11.9
3	34.3	22.0
4	44.6	31.5
5	54.9	42.8
6	54.4	46.0

135 mc

HARMONIC	50v	100v
2	19.5	11.5
3	56.1	33.6
4	63.1	34.2
5	63.1	46.6
6	74.5	47.1

A. Grounded Grid Reference Oscillator Circuit

R_x = 51 ohms

75 mc

HARMONIC	50v	100v
2	28.4	15.0
3	40.9	23.3
4	46.7	34.2
5	47.8	39.9
6	52.1	43.2

135 mc

HARMONIC	50v	100v
2	26.4	10.8
3	37.9	23.1
4	53.0	31.7
5	58.6	39.7
6	60.0	34.2

B. Cathode Coupled Reference Oscillator Circuit

R_x = 51 ohms

NOTE: Figures are in db below the amplitude of the fundamental.

TABLE VI - VARIATION OF HARMONIC CONTENT WITH CHANGES IN PLATE SUPPLY VOLTAGE FOR THE GROUNDED GRID AND CATHODE COUPLED REFERENCE OSCILLATORS

HARMONIC	75 mc 40 ohms	75 mc 51 ohms	75 mc 110 ohms	135 mc 51 ohms	135 mc 68 ohms	135 mc 98 ohms
2	11.0	11.9	13.0	11.5	11.6	12.0
3	20.2	22.0	21.7	33.6	34.7	34.9
4	30.0	31.5	32.8	34.2	32.5	35.4
5	36.1	42.8	40.0	46.6	45.9	46.3
6	44.9	46.0	49.0	47.1	49.0	49.8

A. Grounded Grid Reference Oscillator Circuit

B+ = 100v

HARMONIC	75 mc 40 ohms	75 mc 51 ohms	75 mc 110 ohms	135 mc 51 ohms	135 mc 68 ohms	135 mc 98 ohms
2	16.0	15.0	15.8	10.8	12.3	12.8
3	22.4	21.3	21.7	23.1	24.2	25.1
4	35.0	34.2	34.6	31.7	32.9	35.0
5	43.7	39.9	43.6	39.7	42.9	43.8
6	43.7	43.2	42.8	34.2	35.8	37.7

B. Cathode Coupled Reference Oscillator Circuit

B+ = 100v

NOTE: Figures are in db below the amplitude of the fundamental.

TABLE VII - VARIATION OF HARMONIC CONTENT WITH CHANGES IN CRYSTAL RESISTANCE FOR THE GROUNDED GRID AND CATHODE COUPLED REFERENCE OSCILLATORS.

HARMONIC	75 mc 51 ohms	75 mc 91 ohms	135 mc 51 ohms	135 mc 91 ohms
2	7.0	9.0	12.0	12.3
3	15.6	18.0	21.7	23.4
4	21.2	24.3	36.0	35.3
5	26.8	30.7	36.9	38.9
6	32.0	36.9	49.4	51.4

A. Grounded Grid Reference Oscillator

B+ = 100v

HARMONIC	75 mc 51 ohms	75 mc 91 ohms	135 mc 51 ohms	135 mc 91 ohms
2	16.9	18.1	11.3	11.3
3	24.4	26.5	26.2	27.8
4	32.0	34.9	36.1	38.4
5	40.0	41.6	40.6	41.8
6	45.1	47.4	36.3	36.5

B. Cathode Coupled Reference Oscillator

B+ = 100v

NOTE: Figures tabulated are in db below the amplitude of the fundamental.

TABLE VIII - VARIATION OF HARMONIC CONTENT WITH CHANGES IN CRYSTAL SUBSTITUTION RESISTORS IN THE GROUNDED GRID AND CATHODE COUPLED OSCILLATORS.

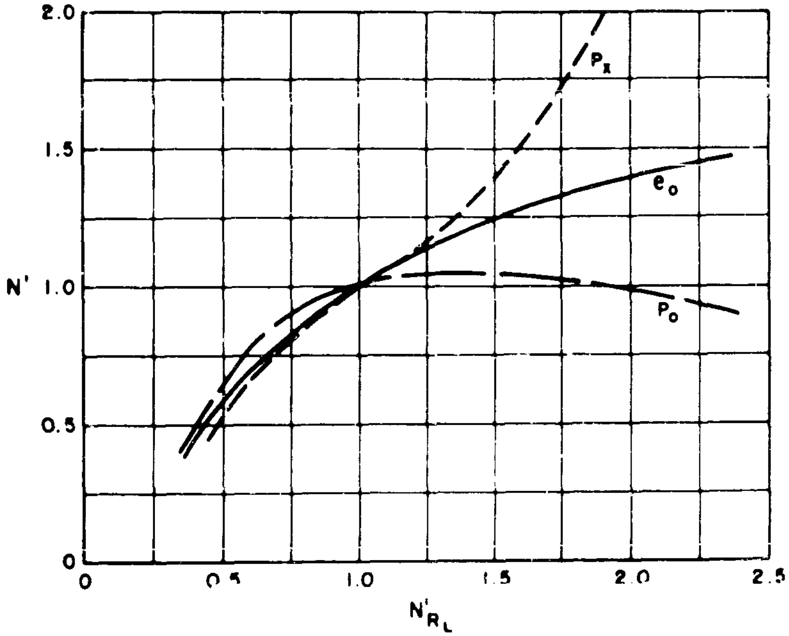


FIG. 25 — NORMALIZED PERFORMANCE VS. LOAD RESISTANCE FOR THE GROUNDED GRID OSCILLATOR

10 – 150 MC

Fig. 25

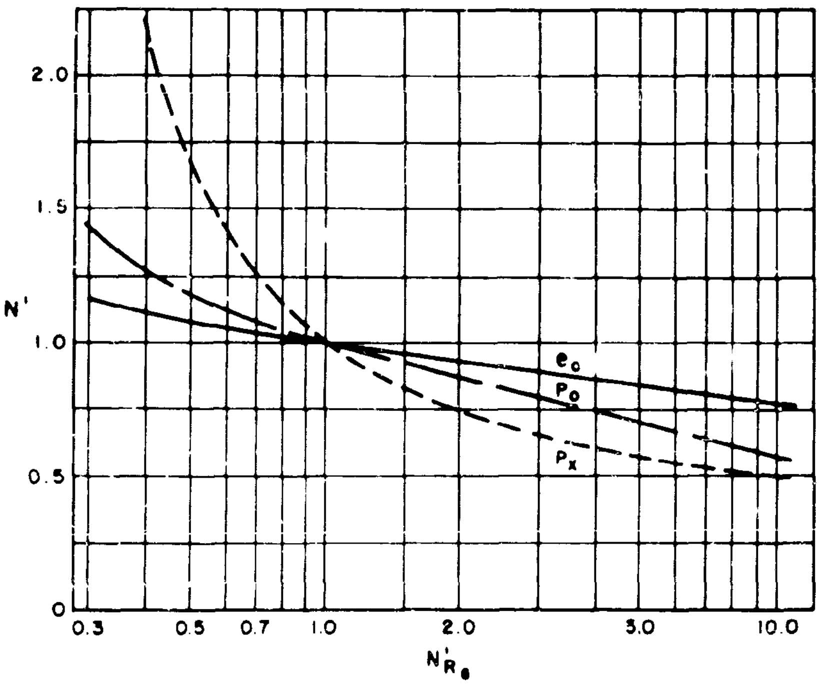


FIG. 26 — NORMALIZED PERFORMANCE VS. GRID RESISTANCE FOR THE GROUNDED GRID OSCILLATOR
10–150 MC

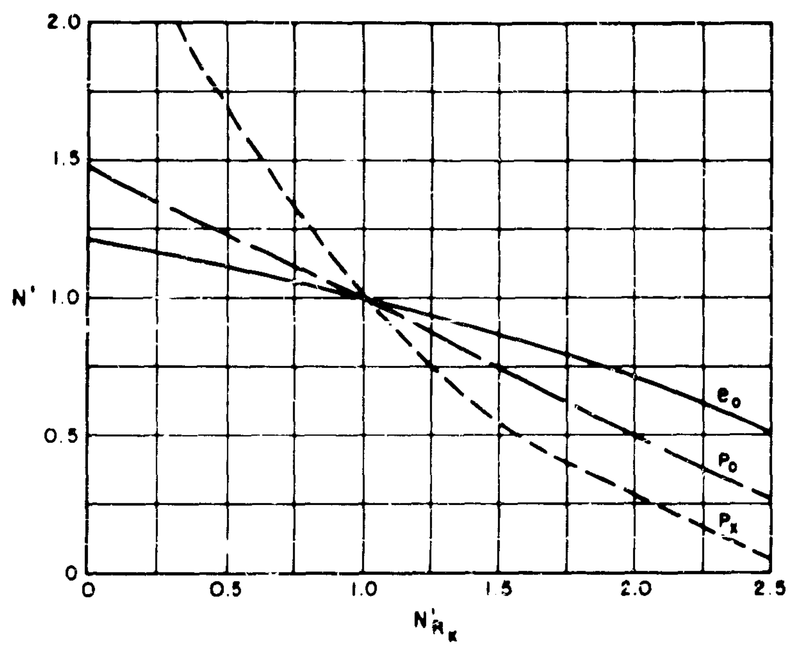


FIG. 27 — NORMALIZED PERFORMANCE VS. CATHODE RESISTANCE FOR Th GROUNDED GRID OSCILLATOR
10 - 150 MC

Fig. 27

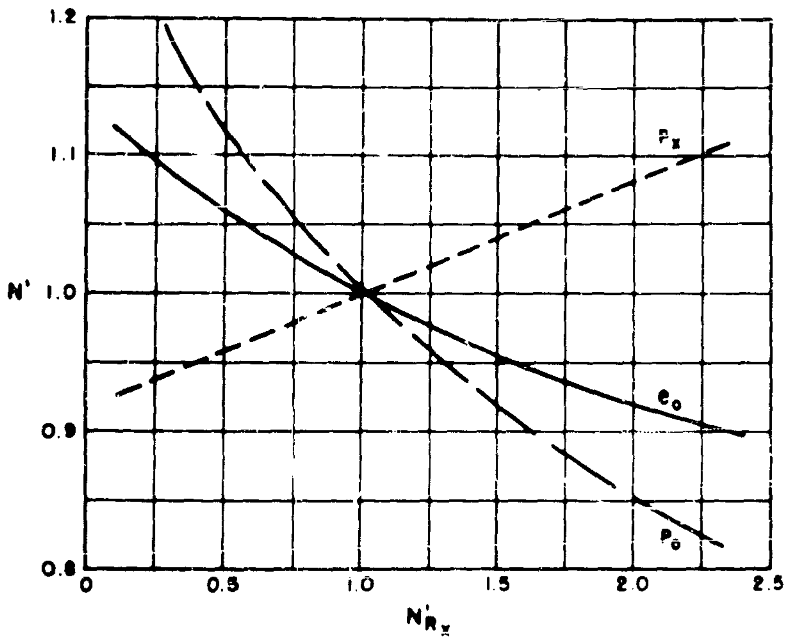


FIG. 28—NORMALIZED PERFORMANCE VS. CRYSTAL RESISTANCE FOR THE GROUNDED GRID OSCILLATOR

10 – 150 MC

Fig. 28

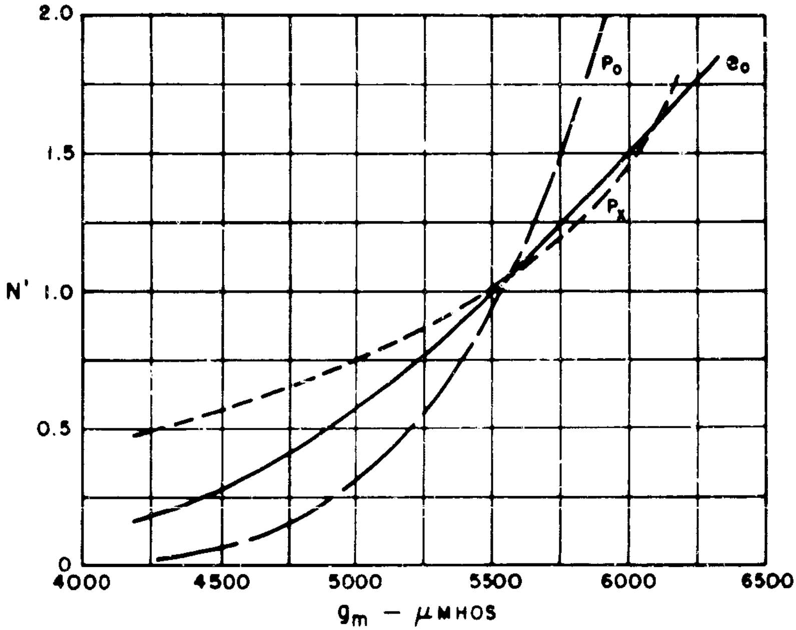


FIG. 29— NORMALIZED PERFORMANCE VS. g_m FOR THE GROUNDED GRID OSCILLATOR
10 – 150 MC

Fig. 29

3. THE CATHODE COUPLED OSCILLATOR 10-75 MC

a. Circuit Description

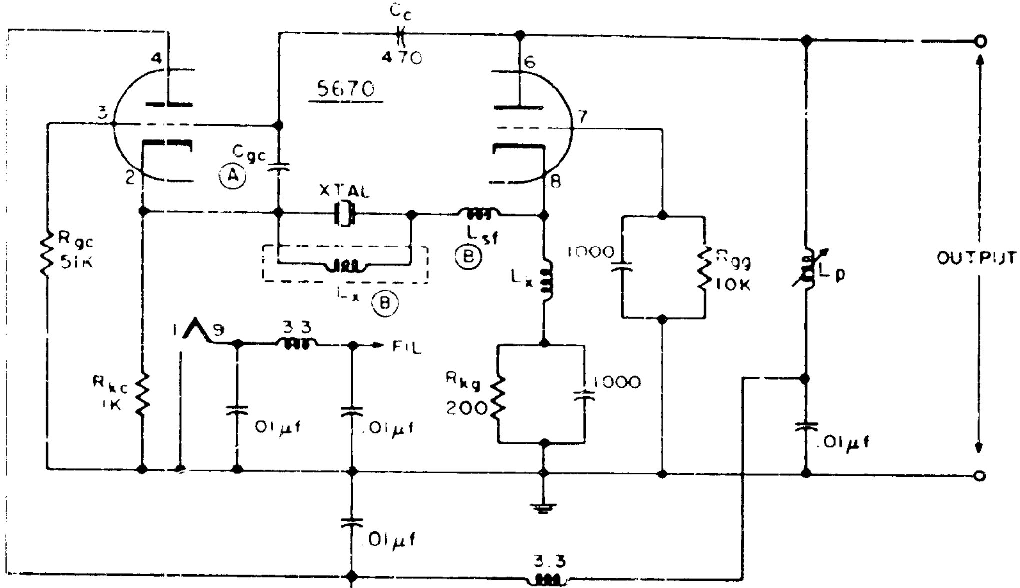
The circuit diagram of the Cathode Coupled oscillator recommended for use in the 10 to 75 mc frequency range is shown in Fig. 30. Coil winding data for this circuit is presented in Table IX and Fig. 31. The value of the coupling capacitor from the output tank to the cathode follower input circuit is smaller than might be expected for normal coupling use. This provides better isolation of the two portions of the circuit, since the grid circuit of the cathode follower is in shunt with the output.

The recommended oscillator circuit, to which all performance and design data is compared, has the following component and circuit parameter values:

R_{gg} = 10K ohms (grounded grid stage grid bias resistor)
R_{kg} = 200 ohms (grounded grid stage cathode bias resistor)
R_{gc} = 51K ohms (cathode follower stage grid bias resistor)
R_{kc} = 1K ohms (cathode follower stage cathode bias resistor)
R_L = 5K ohms (load resistance)
R_x = 25 ohms (series resonant crystal resistance)

The tube type is the 5670 miniature dual triode with a nominal g_m of 5500 μmhos. The bypass, decoupling, and coupling component values are as shown in Fig. 30.

It is to be noted that for operation below 40 mc, L_x, which is used at higher frequencies to cancel C_o of the crystal, is not required. However, it is necessary to include L_{sf}, the series feedback coil, for proper frequency correlation and circuit operation. This coil is not used at frequencies above 40 mc.



INTERNAL SHIELD OF TUBE (PIN #5) IS GROUNDED.

R IN OHMS

C IN $\mu\mu f$

L IN μh

UNLESS OTHERWISE SPECIFIED

SEE TABLE IX AND FIG. 31 FOR VALUES OF L_k, L_p, L_{sf}, AND L_x.

NOTE: (A) – C_{gc} IS $3.0 \mu\mu f$ ABOVE 20mc AND $4.7 \mu\mu f$ BELOW 20mc.

(B) – L_{sf} IS NOT USED ABOVE 40mc
L_x IS NOT USED BELOW 40mc

FIG. 30 — CATHODE COUPLED OSCILLATOR
10 – 75 MC

Freq. mc	Coil -	Coil Form -	Wire Size gage	Coil Length inches	Turns -	L µh	Q -
	L_k	LS6-E	34	5/16	47	17.0	60
10	L_p	LS6-E	34	5/16	47	17.0	60
	L_{sf}	CL-1	-	1.25	-	4.7	-
	L_k	LS6-O	27	1/4	15	1.6	65
30	L_p	LS6-O	27	1/4	15	1.6	65
	L_{sf}	*	27	5/8	14	0.4	90
	L_k	LS6-O	26	1/2	11	0.4	85
60	L_p	LS6-O	26	1/2	11	0.4	85
	L_x	-	32	1/2	15	1.0	5
	L_k	LS6-O	26	7/16	8	0.3	120
75	L_p	LS6-O	26	7/16	8	0.3	120
	L_x	-	32	1/4	21	0.7	10

NOTE: The indicated coil types for L_k and L_p are Cambridge Thermionic Corp. forms, 0.26" O.D., 27/32" long. LS6- is the part number specifying the coil form and size. The suffix designates the core formulation. CL-1 is an International Radio Corp. molded coil. * designates a mica base form, 3/16" O.D., 3/4" long. L_x (at 60 mc) is wound on a 2K, 1 watt carbon composition resistor. At 75 mc, a 1/2 watt resistor is used.

The inductance and Q of all coils were measured at their respective frequencies on a Boonton Radio Corp. Q Meter, Model 160A.

TABLE IX - CATHODE COUPLED OSCILLATOR COIL DATA

10 - 75 mc

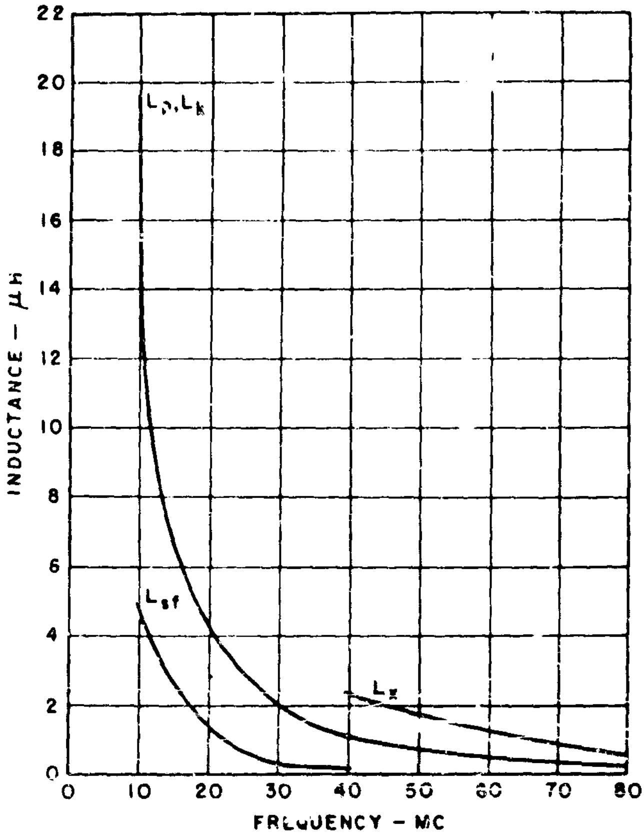


FIG 31 —— INDUCTANCE VS. FREQUENCY FOR THE CATHODE COUPLED OSCILLATOR COILS 10-75 MC

b. Component and Circuit Construction Details

Refer to the comments on component and circuit parameters found in Part A.1.b.

The constructional details of the performance test circuits may be seen in Fig. 32. The photograph shows the layout of a typical 75 mc Cathode Coupled oscillator. The components are labelled according to the schematic of Fig. 30. Note that L_k is a fixed inductance, as is L_x located below the crystal socket.

c. Circuit Tuning Procedure

Refer to the procedure outlined in Part A.1.c. The tuning procedure is similar except that a tap point is not needed on the plate coil.

d. Circuit Performance Characteristics

The circuit as shown in Fig. 30 has been found to provide the most satisfactory performance throughout the frequency range and is recommended for the majority of applications. This circuit should be used without modification wherever possible. In some equipment designs the available supply voltage may not allow the circuit to operate to its full capacity. In such cases design changes may be accomplished, as shown in later examples. Performance graphs for the recommended circuit are accurate to within ten percent. The design graphs yield prediction accuracies of output, with the change of any one component, in the order of 10 to 15 percent. For changes in several components simultaneously, the prediction accuracy decreases. For simultaneous changes in the load and all bias resistors, this figure is about 20 to 25 percent. Crystal drive voltage measurements, made with the assumption of resistive operation of the crystal, revealed prediction accuracies in the order of 20 to 30 percent in the majority of single component changes.

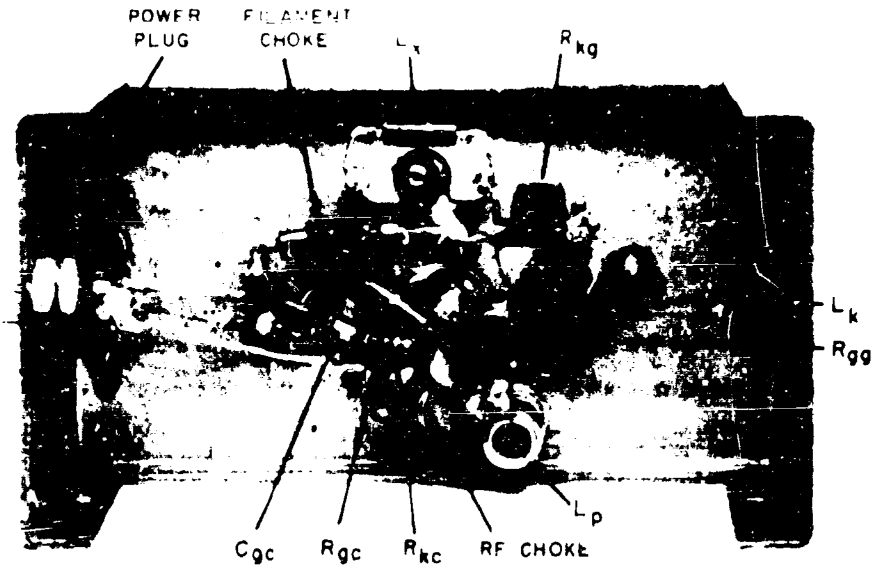


FIG. 32 —— TYPICAL CATHODE COUPLED OSCILLATOR CIRCUIT LAYOUT (75 mc).

Curves of output voltage and power and crystal drive versus frequency of operation are shown in Figs. 33 and 34, respectively. In addition, curves of required values of B and the resultant output for constant values of crystal drive level over the frequency range are presented in Figs. 35 and 36, respectively. The graphs depict performance of a circuit having the component values indicated in Fig. 30. The performance figures obtained from changes in component value are normalized with respect to the recommended circuit figures. The resulting normalized graphs are common to the entire 10 to 150 mc frequency range, and are shown in Figs. 49 through 57, on fold-out pages 102 through 110. These graphs show output voltage, output power, and crystal drive level as a function of the values of R_L, R_{gg}, R_{kg} (DC Coupled), R_{kg} (Capacity Coupled), R_{gc}, R_{kc} (DC Coupled), R_{kc}(Capacity Coupled), R_x, and g_m, respectively. In order to utilize these curves for the design of Cathode Coupled oscillators in the desired frequency range, examples are shown subsequently.

At frequencies in the range of 10 to 40 mc, where L_x is not used, the cathodes are isolated with respect to dc, by the crystal. For this type of operation, the capacity coupled normalized curves, Figs. 52 and 55, should be used. If dc isolation is required, or desirable, at the upper frequency range, a physical capacitor may be inserted in the feedback path and the same figures are used to determine performance.

It is possible to operate the Cathode Coupled circuit over a band of frequencies without retuning the cathode coil. If the frequency of operation is within $\pm$ 20 percent of the fixed-tuned frequency of the cathode coil, the output will vary less than ten percent and the frequency correlation figure will be within ten parts per million from the cathode coil center frequency values. Crystal voltage correlation cannot be obtained since the crystal is not operated at the series resonant frequency. As a result,

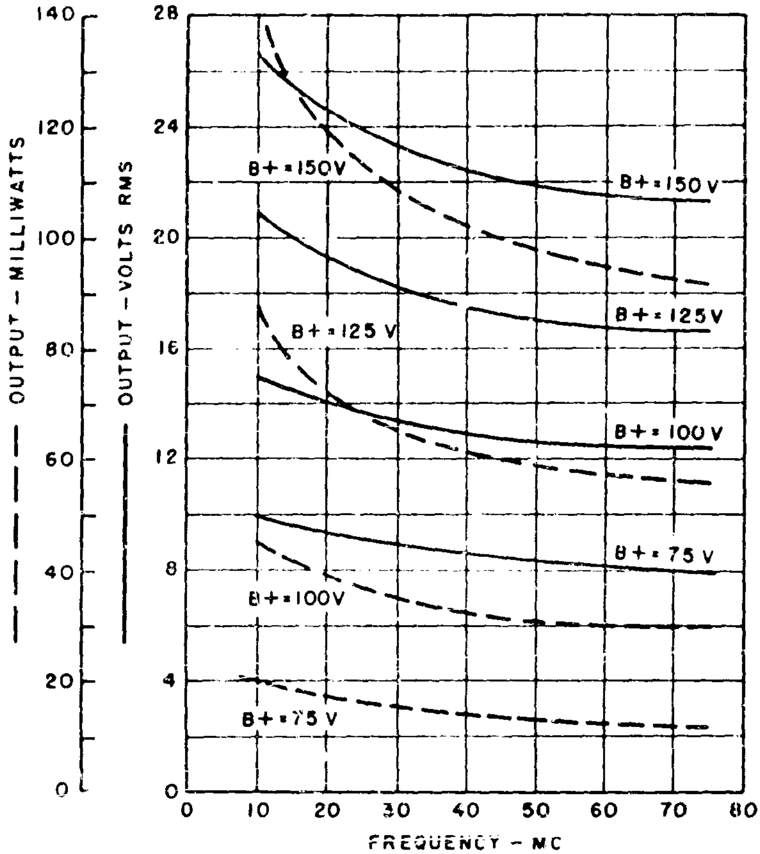


FIG. 3 — OUTPUT VOLTAGE AND POWER VS. FREQUENCY FOR THE CATHODE COUPLED OSCILLATOR 10 – 75 MC

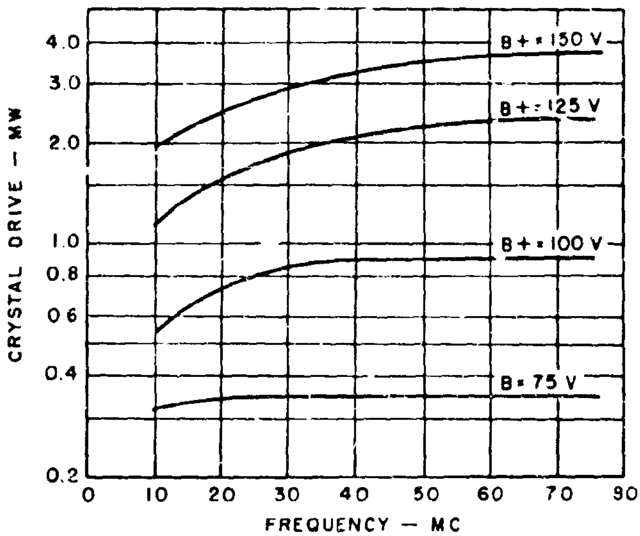


FIG. 34 —— CRYSTAL DRIVE VS. FREQUENCY FOR THE CATHODE COUPLED OSCILLATOR 10 - 75 MC

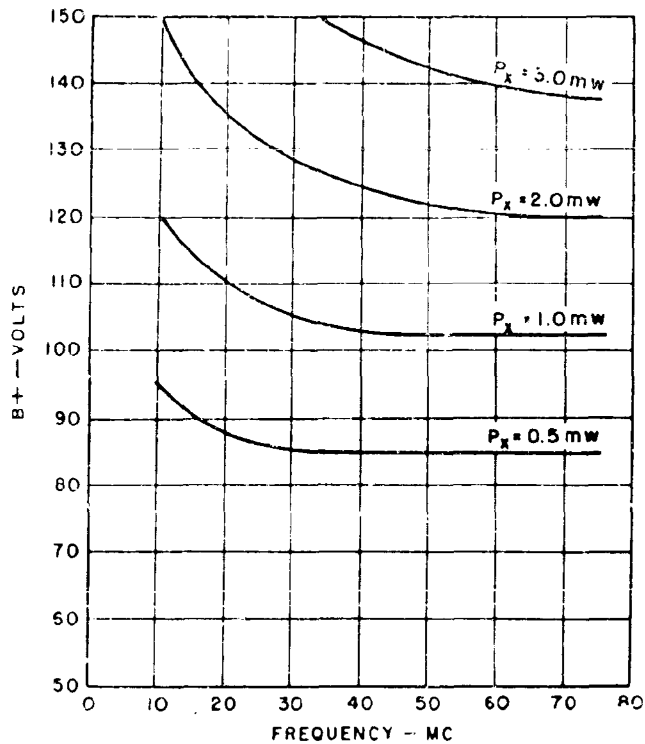


FIG. 35 B+, CONSTANT P_x CURVES FOR THE CATHODE COUPLED OSCILLATOR 10 - 75 MC

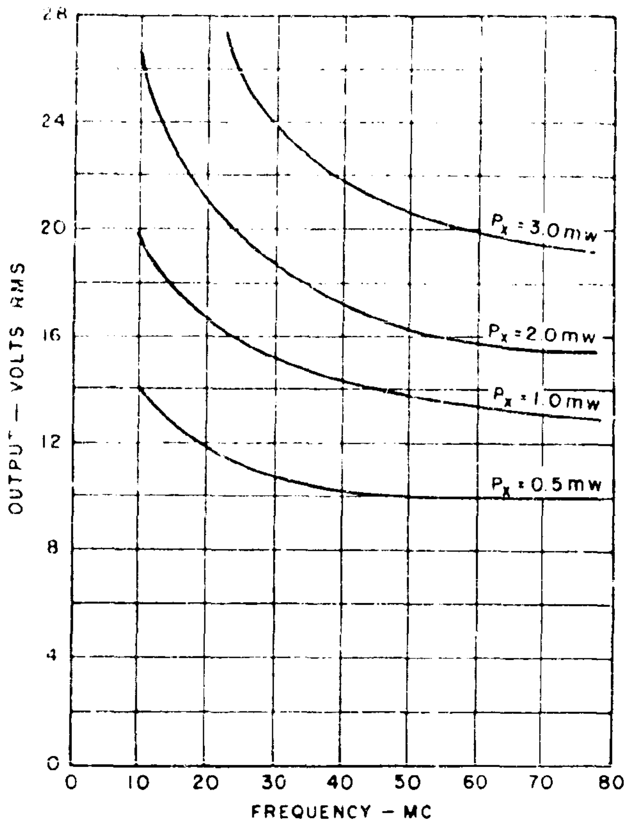


FIG 36 — OUTPUT, CONSTANT P_x CURVES FOR THE CATHODE COUPLED OSCILLATOR 10 – 75 MC power dissipation figures are not easily determined, but lie within the range of values indicated in Fig. 34.

It is recommended that, wherever feasible, the output coupling be adjusted to provide an effective load resistance of 5000 ohms to the oscillator at the frequency of operation. When this is not done, reference must be made to the normalized load resistance graph of Fig. 49. The effect on performance with variations in crystal resistance is shown in Fig. 56, which can be used to indicate the performance when a specific crystal resistance is used or to show the range of performance of typical crystals in the Cathode Coupled oscillator from 10 to 75 mc. Performance is referenced to a crystal resistance value of 25 ohms. Recommended military crystal types which can be used in this application are CR-19/U, CR-24/U, CR-32/U, CR-35/U, CR-52/U, CR-54/U, CR-55/U and CR-56/U. Reference should be made to "MIL-C-3098B Crystal Units, Quartz", for specific crystal information such as maximum resistance limits, physical configuration, and frequency range.

e. Circuit Design Examples and Use of Curves

One of the chief values of the design method presented here is in the prediction of oscillator performance of a given design. At specified frequency and plate supply voltage values, the recommended circuit performance is determined from Figs. 33 and 34. If the output and drive level values are other than those desired, reference is made to Figs. 35 and 36 and/or the normalized curves to determine which circuit parameter may be changed to obtain the necessary results. Any parameter that must remain fixed would eliminate the use of its corresponding performance curve. The normalized factors are obtained by dividing the necessary or desired parameter value by the recommended circuit value and the result applied to the appropriate curve (See Part A.1.e.). Recommended circuit component or parameter values given in this manual should be followed, wherever possible, since the recommended circuit is optimum for typical application. To illustrate the use of the design graphs, the following example is given.

Assume an oscillator is to be designed having the following circuit and performance requirements:

f_n = 60 mc.

B+ = 100 volts

R_L = 4000 ohms

P_x = 2.0 mw (determined from MIL-C-3098B for a particular crystal type)

Reference to Fig. 33 shows that the output is 12.5 volts rms under these conditions. The drive level, from Fig. 34, is 0.9 mw. These figures refer to the recommended circuit. At the required load of 4000 ohms, Fig. 49 shows that for N'_{R_L} = 4000/5000 = 0.8, the normalized output and crystal drive factors N', are about 0.86 each, where 5000 ohms is the reference circuit load resistance. This means that at the required load the output will be 12.5 x 0.86 = 10.8 volts and the drive will be 0.9 x 0.86 = 0.77 mw. It may be desirable to investigate methods of increasing available output and taking advantage of the drive limit. This may be done in a variety of ways. Several methods will be shown here.

The first method depends on the variability of the plate supply voltage. If B+ can be changed, then Figs. 35, 36 and 49 are used to determine performance. For a drive of 2.0 mw, Fig. 35 shows that B+ must be 120 volts for a 60 mc oscillator. From Fig. 36 it is determined that the output voltage is 13.5 volts for this level of drive. This is for the reference circuit. In order to account for the lower load of 4000 ohms, N'_{R_L} = 0.8 and N' = 0.86, as shown in the original example. Since operation at 4000 ohms load reduces the drive by 0.86, a B+ value must be chosen which would drive the reference circuit at 2.0/0.86 = 2.3 mw. This occurs at a B+ of approximately 125 volts. Under these conditions, the output is 16.8 volts. However, the output at a 4000 ohms load would be 16.8 x 0.86 = 14.4 volts.

Additional methods depend on the use of the normalized performance curves. To determine which curves are applicable, a review of the circuit conditions is necessary. With the required load the drive level is 0.77 mw, as determined above. It is desirable to raise this to the nominal drive of 2.0 mw. N' is then 2.0/0.77 = 2.6. Of course, some component change must be effected which will not only produce the desired increase in drive, but will also increase the output, rather than decrease it. Inspection of the normalized performance curves shows that there is no component which will increase the drive by this factor (2.6). However, there is one which does increase the drive and output simultaneously. This is R_{kg} (DC Coupled), shown in Fig. 51. The other components either decrease output with increases in drive or else have negligibly small factors. By extrapolation of the normalized R_{kg} curve, it can be found that the drive increases by a factor of nearly 2.6 when this resistance is zero. For this condition, the output factor is N' = 1.4. Therefore, the output will be 10.8 x 1.4 = 15.2 volts.

The largest output in this case is obtained by making the grounded grid stage cathode bias resistor zero. Similar methods may be applied to those cases where output voltage or power is to remain fixed.

The two graphs of Figs. 56 and 57 show performance variations with crystal resistance and tube transconductance. Little control can be held over these parameters, unless lengthy, selective tests are made. Nevertheless, the graphs are included to indicate their effect on circuit performance. It can be seen that a 100 percent increase in crystal resistance lowers the output by about ten percent and increases the drive by less than five percent.

For a ten percent decrease in g_m the output decreases ten percent and the drive decreases 40 percent. The use of different tube types having approximately the same range of g_m values might necessitate an adjustment in the estimates of circuit stray capacitances, transit time loading, etc.

f. Additional Performance Characteristics

Several additional performance characteristics have been determined and are presented here. The first of these is the stability characteristics of the Cathode Coupled oscillator in the frequency range of 10 to 75 mc. Table X shows the figures for stability with changes in B+ and crystal resistance values. Three crystals operating at each of three frequencies, 10, 30, and 75 mc, are shown. The definitions of Δf_s, etc., as used here, have been discussed in Part A.1.f.

A second performance characteristic is that of frequency variation with temperature (See Fig. 20). Crystal unit specifications for this frequency range call for a maximum deviation from the nominal frequency of 50 ppm throughout the temperature range of -55°C to +90°C. However, typical changes from the mean frequency values encountered for these units are between 15 and 25 ppm. Temperature coefficients of circuit component parts will cause the operating frequency to deviate further. Circuit temperature-frequency variations are less than 40 ppm and when combined with the maximum crystal unit deviation totals less than 90 ppm for typical conditions. Inclusion of variations due to ten percent B+ and filament voltage changes raises this figure to a maximum of 100 ppm. However, values for typical operation are usually less than 75 ppm.

Harmonic content in the output of these circuits is similar in characteristics to those found for the Grounded Grid oscillator (see, also, Tables VI through VIII) discussed in Part A.1.f.

10 mc					30 mc					75 mc				
R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f
23	75	- 7.0	-	-	16	75	- 4.6	-	-	22	75	-12.4	-	-
	100	- 6.2	0.5	-		100	- 2.6	1.5	-		100	- 4.2	2.5	-
	125	- 5.9	-	-		125	+ 1.6	-	-		125	- 2.0	-	-
	150	- 4.1	0.7	-		150	+ 2.8	2.3	-		150	+ 1.1	3.2	-
28	75	- 2.6	-	-	26	75	+ 0.1	-	-	40	75	- 3.0	-	-
	100	- 2.1	0.3	0.5		100	+ 0.4	1.8	-		100	- 1.0	2.5	-
	125	- 1.5	-	-		125	+ 0.9	-	-		125	+ 3.4	-	-
	150	- 0.4	0.3	-		150	+ 2.2	2.7			150	+ 6.4	4.4	-
33	75	+ 6.9	-	-	58	75	+ 5.3	-	-	51	75	+ 0.6	-	-
	100	+ 6.6	0.1	-		100	+ 6.1	1.6	0.5		100	+ 3.0	1.3	0.5
	125	+ 4.8	-	-		125	+ 7.7	-	-		125	+ 4.6	-	-
	150	+ 4.8	0.7	-		150	+10.3	2.0	-		150	+ 4.9	1.5	-

R_x in ohms, B+ in volts and Stability figures in parts per million

TABLE X - **STABILITY CHARACTERISTICS OF THE CATHODE COUPLED OSCILLATOR**

10 - 75 mc

Inspection of Fig. 50 indicates that as the value of the grounded-grid grid-bias resistor is decreased the desirable performance trend of increased output and decreased drive level occurs. It is not recommended, however, that the grid actually be shorted to ground, since this has an adverse effect on the frequency stability and the correlation is very poor.

It may be desirable, in some cases, to utilize the circuit with an untuned cathode. Although the use of a tuned cathode coil provides higher oscillator output voltages, the advantages of the untuned case are the elimination of the component part itself, a simpler tuning procedure, and broadband, rather than fixed, frequency operation. Information on the Cathode Coupled oscillator operating with an untuned cathode circuit is therefore presented. In general, some component changes are necessary in the reference circuit. Typical values for circuits operating in the frequency bands of 10 to 20, 20 to 40, and 40 to 75 mc are listed below, where resistance is in ohms and capacitance is in mmfd. All other components remain the same as in the reference circuit. It should be noted that for this application, L_{gf} is not used.

	Frequency Ranges		
Component	10 to 20 mc	20 to 40 mc	40 to 75 mc
R_{kg}	1K	560	1K
R_{kc}	1K	620	100
C_{gc}	10	7.5	4.7

R_{kg} is changed to 10K ohms for operation throughout the frequency range.

Performance curves for the oscillator at various levels of plate supply voltage are shown in Fig. 57. Operation at frequencies above 75 mc is not recommended.

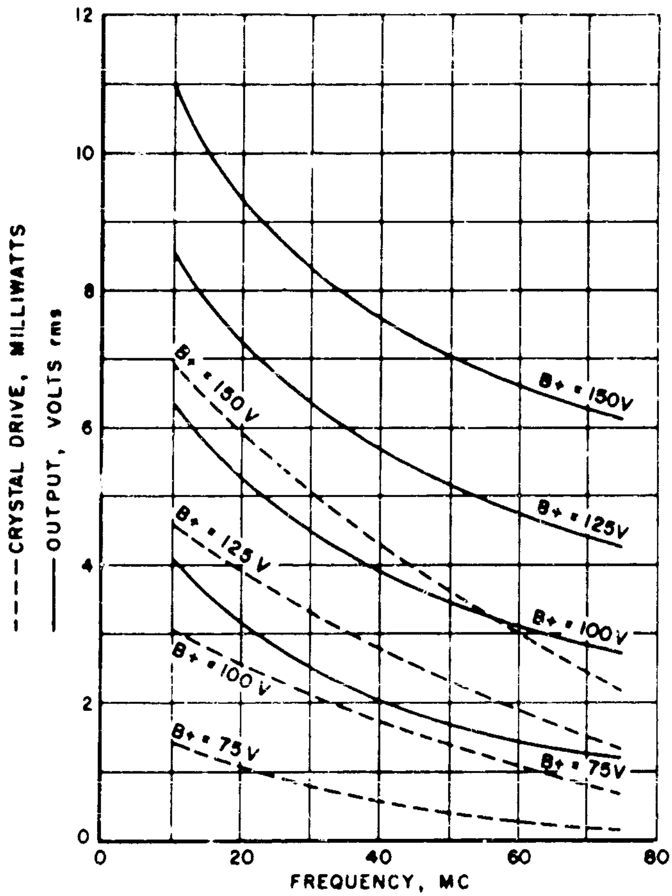


FIG. 37-PERFORMANCE OF THE CATHODE COUPLED OSCILLATOR WITH UNTUNED CATHODE CIRCUIT (GROUNDED GRID STAGE)

10-75 MC

Frequency correlation is good, provided the component values suggested above are used. Frequency stability is comparable to that of the tuned cathode circuit; Δf_b ranges from less than one part per million at 10 mc to less than four parts per million at 75 mc.

4. THE CATHODE COUPLED OSCILLATOR - 75-150 MC

a. Circuit Description

The circuit diagram of the Cathode Coupled oscillator recommended for use in the 75 to 150 mc frequency range is shown in Fig. 38. Coil winding data is presented in Table XI and Fig. 39.

The oscillator circuit has the component and circuit parameter values given in Part A.3.a. except for the reference value of R_x, which is 51 ohms for this frequency range.

b. Component and Circuit Construction Details

In general, the discussion of components and circuit construction details given in Part A.1.b. applies here. However, greater care must be given to lead dress, grounding, and parts placement at these higher frequencies.

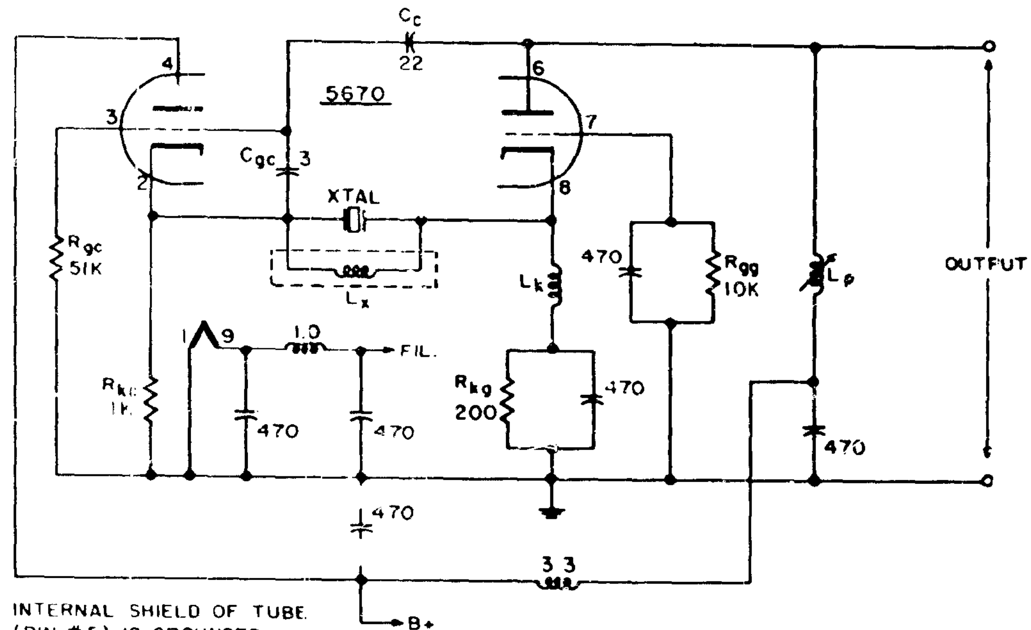
c. Circuit Tuning Procedure

See Part A.1.c. The tuning procedure is similar except that a tap point is not needed on the plate coil.

d. Circuit Performance Characteristics

The circuit as shown in Fig. 38 has been found to provide the most satisfactory performance throughout the frequency range and is recommended for the majority of applications. This circuit should be used without modification wherever possible. In some equipment designs the available supply voltage may not allow the circuit to operate at its full capacity. In such cases design changes may be accomplished as shown in later examples.

Curves of output voltage and power, and crystal drive versus frequency of operation are shown in Figs. 40 and 41, respectively. In addition, curves of required values of B+ and the resultant output for constant values of crystal drive level over the frequency range are presented in Figs. 42 and 43, respectively. The graphs depict performance of a circuit having the component



INTERNAL SHIELD OF TUBE (PIN #5) IS GROUNDED.

R IN OHMS
C IN $\mu\mu f$
L IN μh
UNLESS OTHERWISE SPECIFIED

SEE TABLE XI AND FIG. 39 FOR VALUES OF L_k, L_p, AND L_x.

FIG 38 — CATHODE COUPLED OSCILLATOR
75 – 150 MC

Freq.	Coil	Coil Form	Wire Size	Coil Length	Turns	L	Q
mc	-	-	gage	inches	-	µH	-
	L_x	-	32	1/4	21	.670	10
75	L_k	LS6-0	26	7/16	8	.360	120
	L_p	LS6-0	26	7/16	8	.265	125
	L_x	-	27	1/4	16	.370	5
105	L_k	LS6-0	22	5/16	6	.190	120
	L_p	LS6-0	22	5/16	5	.140	120
	L_x	-	24	3/8	10	.210	25
135	L_k	LS6-0	20	1/4	4	.110	165
	L_p	LS6-0	20	1/4	3	.075	110
	L_x	-	24	5/32	8	.180	33
150	L_k	LS6-0	22	1/4	3	.090	125
	L_p	LS6-0	22	3/16	3	.065	100

NOTE: L_x is wound on a 2K, 1/2 watt carbon composition resistor. The indicated coil types for L_k and L_p are Cambridge Thermionic Corp. forms, 0.26" O.D., 27/32" long. LS6- is the part number specifying the coil form type and size. The suffix designates the core formulation.

The inductance and Q of all crystal coils, L_x, were measured at 50 mc on the Boonton Radio Corp. Q Meter, Model 160A. The inductance and Q of L_k and L_p were measured at their operating frequencies on the Boonton Radio Corp. Q Meter, Model 170A.

TABLE X - CATHODE COUPLED OSCILLATOR COIL DATA

75 - 150 mc

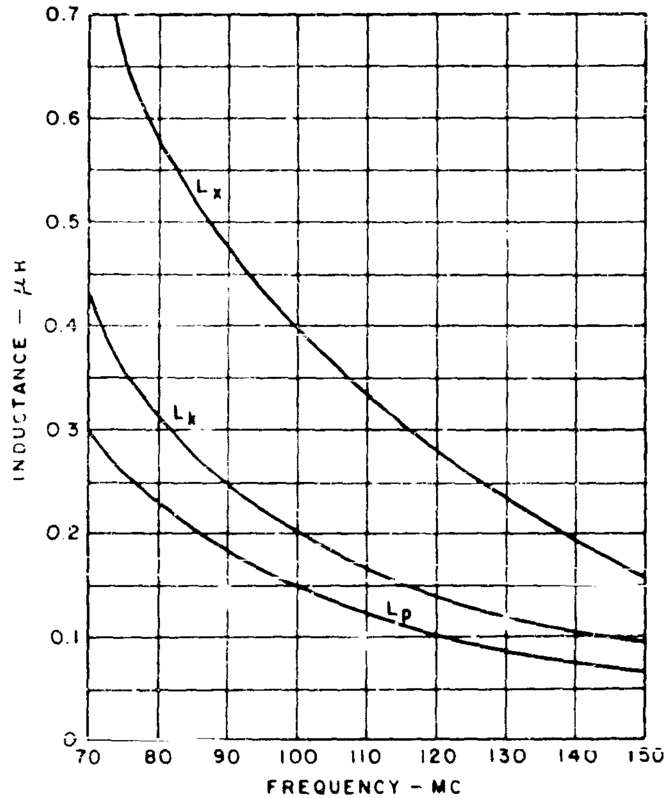


FIG 39 — INDUCTANCE VS. FREQUENCY FOR THE CATHODE COUPLED OSCILLATOR COILS 75 – 150 MC

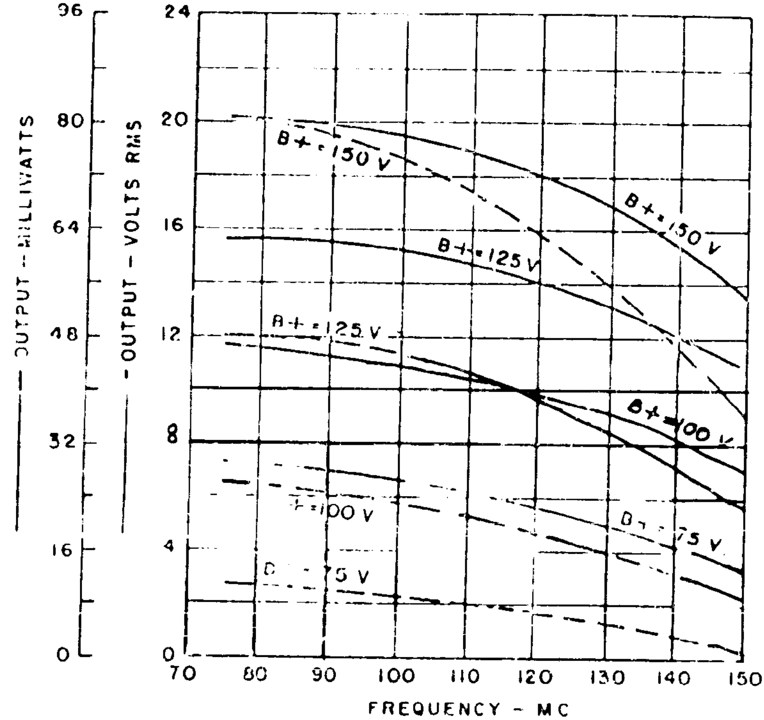


FIG. 40 — OUTPUT VOLTAGE AND POWER VS FREQUENCY FOR THE CATHODE COUPLED OSCILLATOR 75 - 150 MC

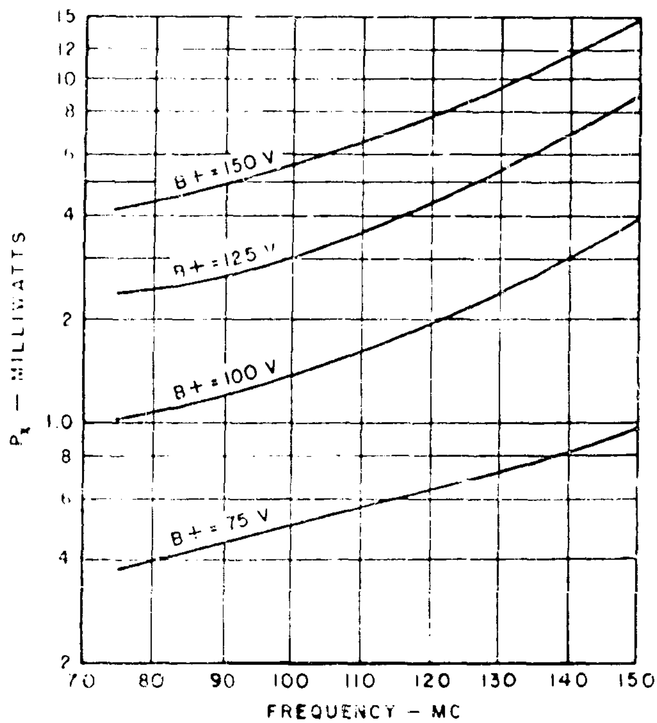


FIG 41 —— CRYSTAL DRIVE VS FREQUENCY FOR THE CATHODE COUPLED OSCILLATOR 75 – 150 MC

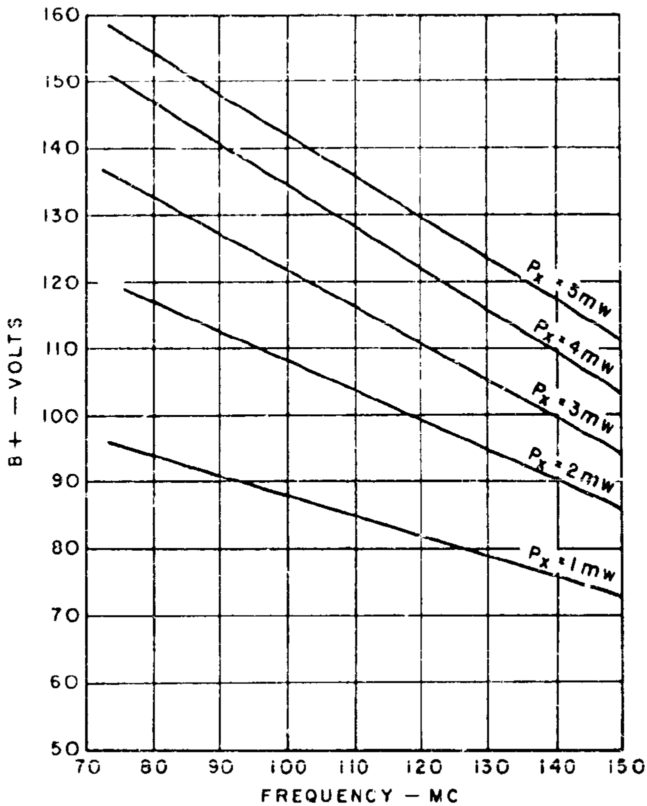


FIG 42 B+, CONSTANT P_x CURVES FOR THE CATHODE COUPLED OSCILLATOR 75-150 MC

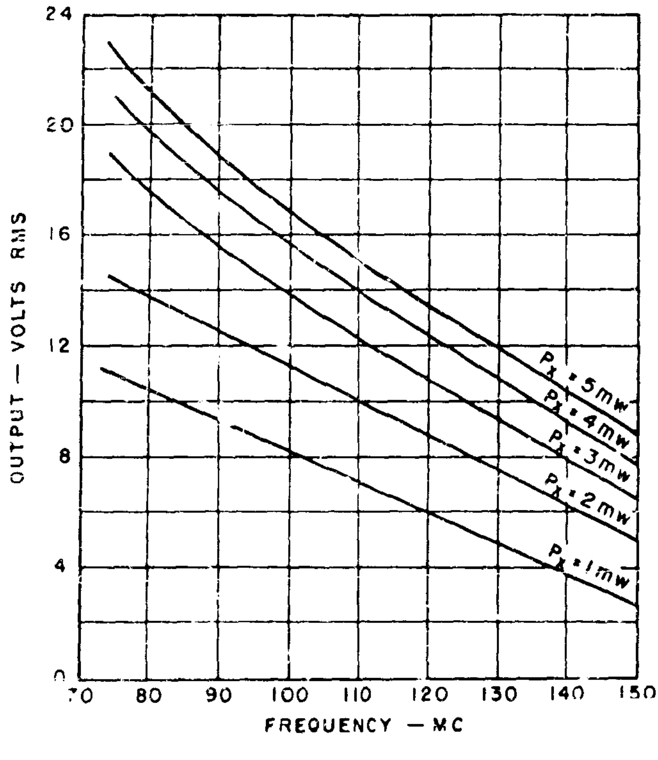


FIG 43 — OUTPUT, CONSTANT P_x CURVES FOR THE CATHODE COUPLED OSCILLATOR 75-150 MC values indicated in Fig. 38. The performance figures obtained from changes in component value are normalized with respect to the recommended circuit figures. The resulting normalized graphs are common to the entire 10 to 150 mc frequency range, and are shown in Figs. 49 through 57 on fold-out pages 102 through 110. These graphs show output voltage, output power, and crystal drive level as a function of the values of R_L, R_{gg}, R_{kg} (DC Coupled), R_{kg} (Capacity Coupled), R_{gc}, R_{kc} (DC Coupled), R_{kc} (Capacity Coupled), R_x, and g_m, respectively.

Figure 44 combines the effect on output of increasing or decreasing R_L, R_{gg}, R_{kg}, R_{gc}, and R_{kc} simultaneously and by the same percentage. This figure is obtained by taking the product of the average output factors, represented by the curves in Figs. 49, 50, 51, 53 and 54, resulting from the same percentage change for each of the resistences.

The graph affords a check on the reliability of the design data for a wide range of operating conditions. If, for example, these five components are each increased by a factor of 2.0 over the reference value, it can be seen from the graph that the output should decrease to 85 percent of the reference value.

Results of circuit measurements to check this are shown in Table XII. Here, two resistance factor values, 0.65 and 1.66, were used. This means that the pertinent resistance values in the new circuit are the stated percentages of the reference circuit values. From Fig. 44, the corresponding output factors, N', are 0.84 and 0.98, respectively. A circuit was constructed whose components corresponded to these values and output was measured at four levels of supply voltage. These output measurements are tabulated in the column headed "e_o". The theoretical changes are listed under the column headed "$N'e_o'$" where e_o' is the reference circuit output and N' is the output

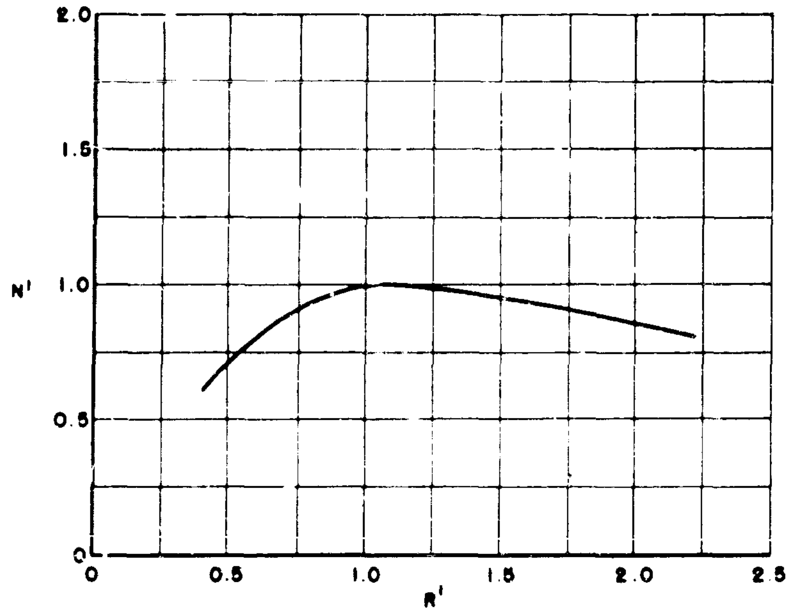


FIG. 44 — NORMALIZED CURVE FOR COMBINED CHANGE IN GRID, CATHODE AND LOAD RESISTANCES FOR THE CATHODE COUPLED OSCILLATOR.

Circuit Conditions			75 mc		105 mc		135 mc		150 mc	
R'	M'	B+	e_o	$M'e'_o$	e_o	$M'e'_o$	e_o	$M'e'_o$	e_o	$M'e'_o$
0.65	0.84	75	4.6	6.1	5.6	5.3	4.3	3.9	2.7	3.0
		100	7.8	9.9	9.1	8.8	7.5	7.1	6.2	5.9
		125	11.1	13.3	12.9	12.6	10.7	10.6	9.6	9.2
		150	14.7	16.9	16.3	16.0	13.7	13.4	12.6	11.3
1.66	0.98	75	9.4	7.2	8.6	6.2	6.5	4.5	2.3	3.5
		100	14.6	11.6	13.2	10.3	10.2	8.3	5.4	6.9
		125	19.9	15.5	17.5	14.7	15.9	12.3	8.5	10.8
		150	25.0	19.7	21.5	18.6	17.3	15.7	11.3	13.2

TABLE XII - COMPARISON OF PREDICTED AND MEASURED PERFORMANCE OF THE CATHODE COUPLED OSCILLATOR CIRCUIT factor resulting from the use of the information in Fig. 44.

The effect on output voltage resulting from the use of different tube types and having a range of g_m values is shown in Figs. 45 through 48, inclusive, where the frequencies of operation were 75, 105, 135, and 150, respectively. Each graph represents the output obtained from the reference circuit using the 5670 miniature dual triode and the 6021 subminiature dual triode. Three 5670 tubes, having different g_m values, were used. The reference circuit component tube was a 5670 having a measured g_m of 5800 micromhos for the section used in the grounded grid stage and 5400 micromhos for the section used in the cathode follower stage. All values of g_m were determined with a Hickok Model 533 Mutual Transconductance Tester under standard test conditions.

Figure 57 combines the information of Figs. 45 through 48 to show the general effects of g_m on output. At each frequency, and for several values of B+, the output voltages for the various tubes were compared to the output obtained for the reference circuit under the same operating conditions. The averages of these values were then plotted against the g_m of the tubes to obtain the given curve. Since output varies directly with the transconductance of the grounded grid amplifier tube section the g_m values for this stage were used in Fig. 57.

In order to utilize these curves for the design of the Cathode Coupled oscillator in the desired frequency range, examples are shown below.

Recommended military crystal types that may be used in this application are CR-54/U and CR-56/U. The specifications on these units cover frequencies up to and including 87 mc. Maximum crystal resistances used at 75 and 105 mc were 60 ohms. Maximum resistance used at 135 mc and 150 mc was 100 ohms.

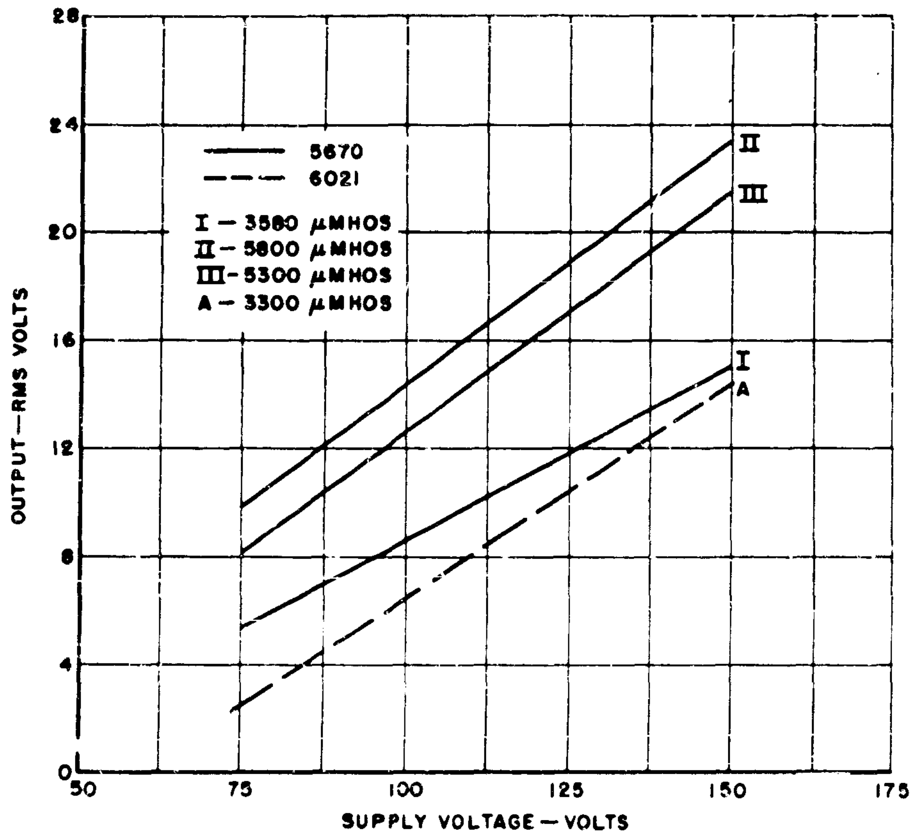


FIG. 45. OUTPUT – g_m CHARACTERISTICS FOR THE CATHODE COUPLED OSCILLATOR AT 75 MC.

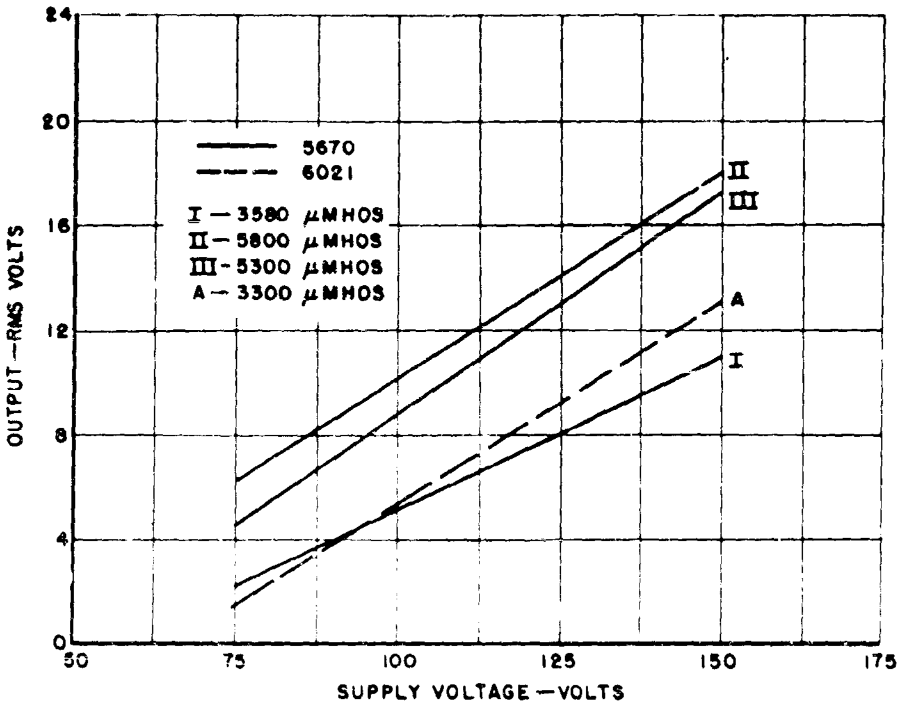


FIG. 46. OUTPUT – g_m CHARACTERISTICS FOR THE CATHODE COUPLED OSCILLATOR AT 105 MC.

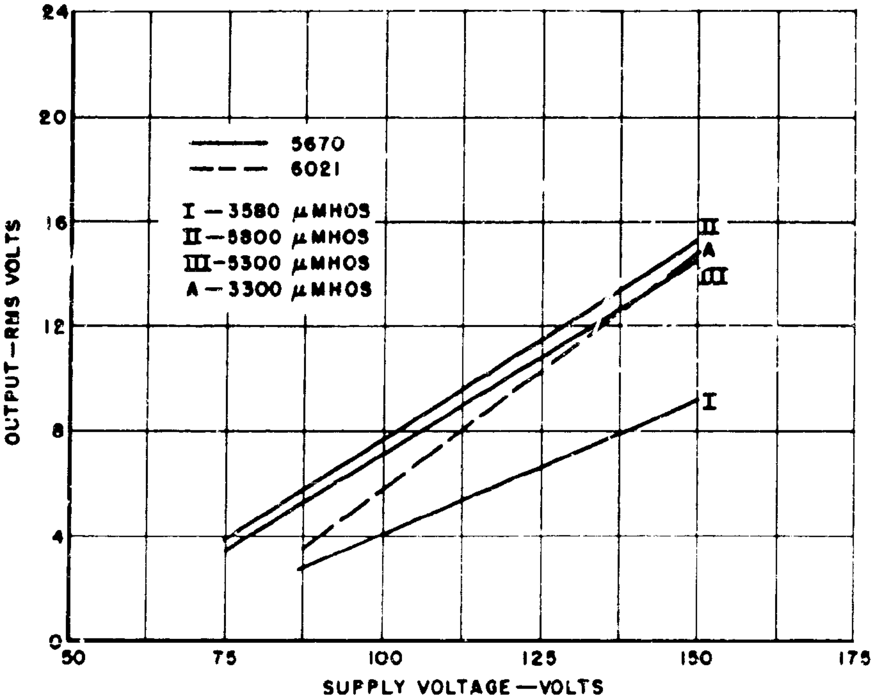


FIG. 47. OUTPUT − g_m CHARACTERISTICS FOR THE CATHODE COUPLED OSCILLATOR AT 135 MC.

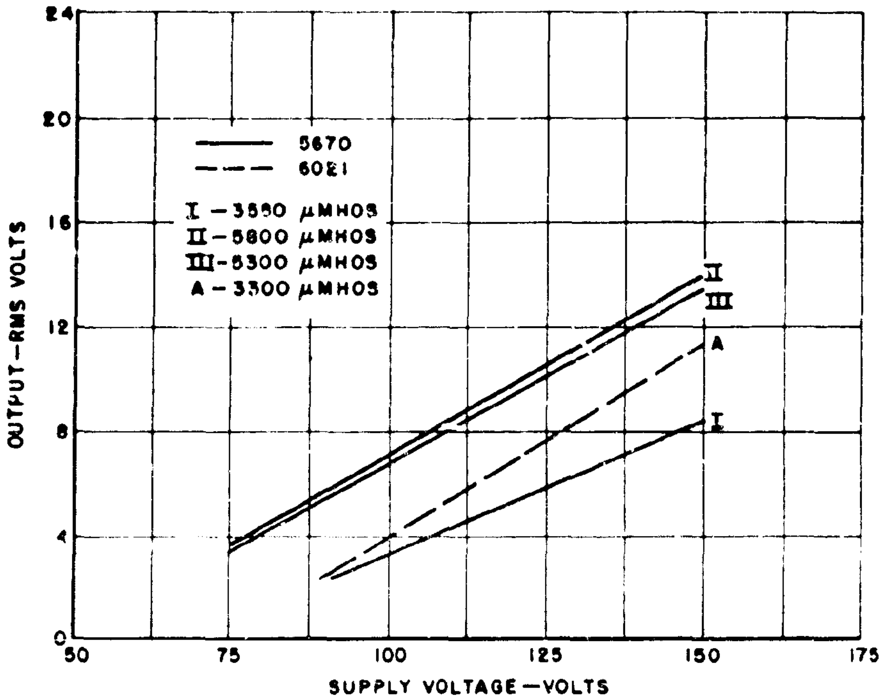


FIG. 48. OUTPUT – g_m CHARACTERISTICS FOR THE CATHODE COUPLED OSCILLATOR AT 150 MC.

Although MIL-C-3098B does not cover crystals operating above 87 mc, available units and USASEL recommendations indicate a maximum crystal resistance of 60 ohms up to and including 125 mc and a maximum of 100 ohms to 150 mc. Although good quality units were available for the present investigations up to 150 mc, one unit, which had a series resonant resistance of 160 ohms, has been included in the data.

Of the crystals available, the spread in crystal resistance at certain frequencies is limited. In order to expand the range, resistor networks were used in the circuit as substitution elements and performance measurements were made. Where resistor networks were used in place of existing crystals, no appreciable change in voltage was noted, provided proper reactive compensation of the resistors was made. In this manner, a wide range of crystal resistances were made available throughout the frequency range.

e. Circuit Design Examples and Use of Curves

To illustrate the use of the design graphs, the following example is given, using the format of Part A...e.

Assume an oscillator is to be designed having the following circuit and performance requirements:

f_n = 105 mc

B+ = 100 volts

R_L = 4000 ohms

P_x = 2.0 mw

The 2.0 mw drive level figure is determined from general MilSpecs for crystals in this frequency range, or from consideration of frequency stability for those units not given in MIL-C-3098B.

Reference to Fig. 40 shows that at a frequency of 105 mc and a B+ of 100 volts, the output of the recommended circuit is approximately 10.5 volts rms. The crystal drive, from Fig. 41, is found to be 1.5 mw. With the required load of 4000 ohms, reference to Fig. 49 shows that for K'_{R_L} = 4000/5000 = 0.8 the normalized output and crystal drive factors, N', are 0.86 each, where 5000 ohms is the reference circuit load resistance. This means that at the required load of 4000 ohms, the output will be 10.5 x 0.86 = 9.0 volts and the drive will be 1.5 x 0.86 = 1.28 mw. Since the nominal allowable crystal drive is 2.0 mw, it may be desirable to investigate methods of increasing available output and take advantage of the drive limit. This may be done in several ways, of which examples will be presented here.

One method depends on the variability of the plate supply voltage. If the B+ can be changed, then Figs. 42 and 43 are used. For a drive of 2.0 mw, it can be seen from Fig. 42 that the B+ must be 106 volts at 105 mc. From Fig. 43 it is determined that the output voltage is 10.5 volts for this level of drive. However, this is for the reference circuit. In order to account for the lower load of 4000 ohms, K'_{R_L} = 0.8 and N' = 0.86, as shown in the original example above. Since operation at 4000 ohms load reduces the drive by 0.86, a B+ value must be found which would drive the reference circuit at 2.0/0.86 = 2.33 mw. This occurs at a B+ of approximately 108 volts, found by use of Fig. 42. Under these conditions, the output is 11.5 volts. However, the output at a load of 4000 ohms would be 11.5 x 0.86 = 9.9 volts.

A second method depends on the normalised performance curves. To determine which curve is applicable, a review of the circuit conditions is required. With the stated load the drive level is 1.28 mw, as determined above. It is desirable to raise this to the nominal value of 2.0 mw. N' is then 2.0/1.28 = 1.56. It is necessary to find a component which, when changed, will increase the drive to this level and also increase the available output voltage. Inspection of the normalized curves shows that the only component capable of this change is R_{kg} (DC Coupled), Fig. 51. The N' = 1.56 factor can be obtained at $N'_{R_{kg}}$ of 0.6, or 200 x 0.6 = 120 ohms. The output factor, N', is found to be 1.2. The resulting output voltage is then 9.0 x 1.2 = 10.8 volts. The other components either decrease output with an increase in crystal drive or provide negligibly small performance changes.

Comparison of methods in this case shows that a change in B+ produces the greater output. Similar methods may be applied in those instances where output voltage or power are to remain fixed. A generalized outline of the design procedure is given in Part A.3.e. However, for this frequency range, performance of the recommended circuit is determined from Figs. 40 and 41, and design changes may be made by reference to Figs. 42 and 43, and/or the normalized curves.

f. Additional Performance Characteristics

Several additional performance characteristics have been determined and are presented here. The first of these is the stability characteristics of the Cathode Coupled oscillator in the frequency range of 75 to 150 mc. Table XIII shows the figures for stability with changes in B+ and filament voltage. The correlation figure is also given for a range of B+ and crystal resistance values. Three crystals operating at each of four frequencies, 75, 105, 135, and 150 mc are shown. The definitions of Δf_s, etc., as used here, have been discussed in Part A.1.f.

A second performance characteristic is the change in frequency with variations in temperature (See Figs. 21 through 24). Complete specifications on the crystals are not available for this frequency range, however, for the -55°C to 90°C range, a maximum nominal deviation of 50 ppm for the crystal

75 mc					105 mc					135 mc					150 mc				
R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f	R_x	B+	Δf_s	Δf_b	Δf_f
22	75	-12.4	-	-	33	75	- 3.6	-	-	51	75	- 6.1	-	-	53	75	- 8.1	-	-
	100	- 4.2	2.5	-		100	+ 2.5	5.8	-		100	- 4.9	4.2	0.6		100	- 4.2	5.0	0.5
	125	- 2.0	-	-		125	+14.6	-	-		125	- 1.7	-	-		125	- 3.7	-	-
	150	+ 1.1	3.2	-		150	+18.8	5.8	-		150	+ 1.5	4.6	-		150	- 2.2	6.3	-
40	75	- 3.0	-	-	41	75	- 6.6	-	-	68	75	- 5.8	-	-	68	75	-12.4	-	-
	100	- 1.0	2.5	-		100	- 1.8	2.5	-		100	- 2.5	7.6	-		100	- 7.6	5.4	-
	125	+ 3.4	-	-		125	- 0.1	-	-		125	- 0.1	-	-		125	- 5.4	-	-
	150	+ 8.4	4.4	-		150	+ 3.0	3.1	-		150	+ 5.4	8.9	-		150	- 0.5	6.0	-
51	75	+ 0.6	-	-	46	75	- 5.0	-	-	98	75	+ 0.1	-	-	91	75	-15.7	-	-
	100	+ 3.0	1.3	0.5		100	+ 3.7	5.2	0.1		100	+ 6.8	5.1	-		100	-11.6	9.3	-
	125	+ 4.6	-	-		125	+ 5.7	-	-		125	+14.0	-	-		125	- 7.2	-	-
	150	+ 4.9	1.5	-		150	+11.9	6.5	-		150	+18.7	9.6	-		150	+ 0.6	6.7	-

R_x in ohms, B+ in volts and Stability figures in parts per million

TABLE XIII- STABILITY CHARACTERISTICS OF THE CATHODE COUPLED OSCILLATOR

75 - 150 mc

is assumed. Typical deviations from the mean values encountered for these units are between 15 and 25 ppm. Temperature coefficients of circuit component parts will cause the operating frequency to deviate further. Circuit temperature-frequency variations are less than 40 ppm, and when combined with the maximum crystal unit deviation totals less than 90 ppm for typical conditions. Inclusion of variations due to ten percent B+ and filament voltage changes raises this figure to a maximum of 100 ppm. However, typical operation yields values that are less than 75 ppm.

Harmonic content in the output of these circuits is similar in characteristics to those found for the Grounded Grid oscillator, discussed in Part A.1.f., where detailed information is found in Tables VI through VIII.

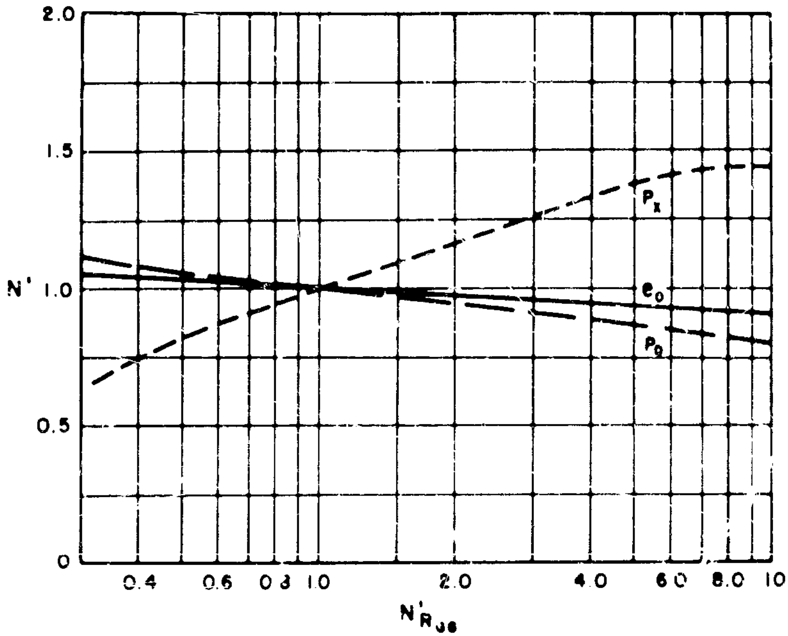


FIG. 50— NORMALIZED PERFORMANCE VS. GROUNDED GRID - GRID BIAS RESISTANCE FOR THE CATHODE COUPLED OSCILLATOR 10 - 150 MC

Fig. 50

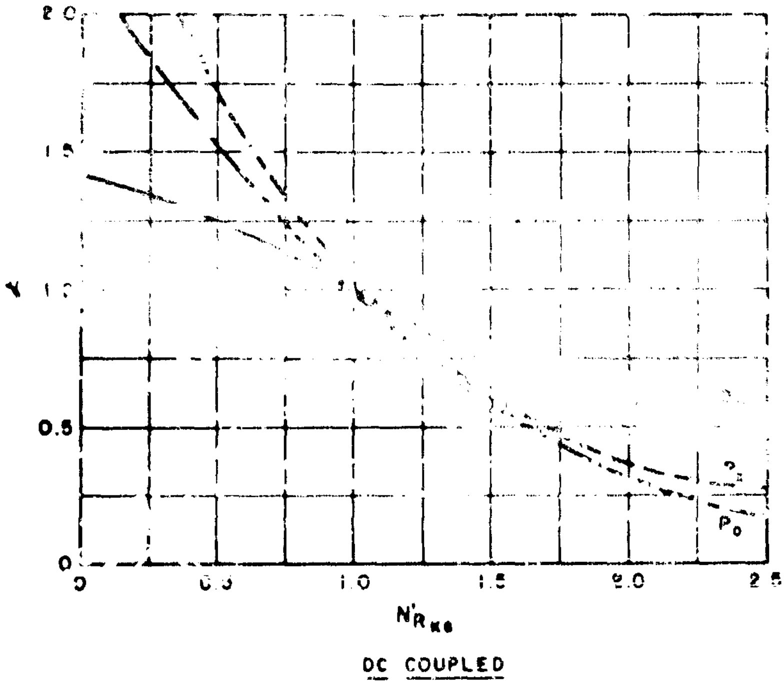
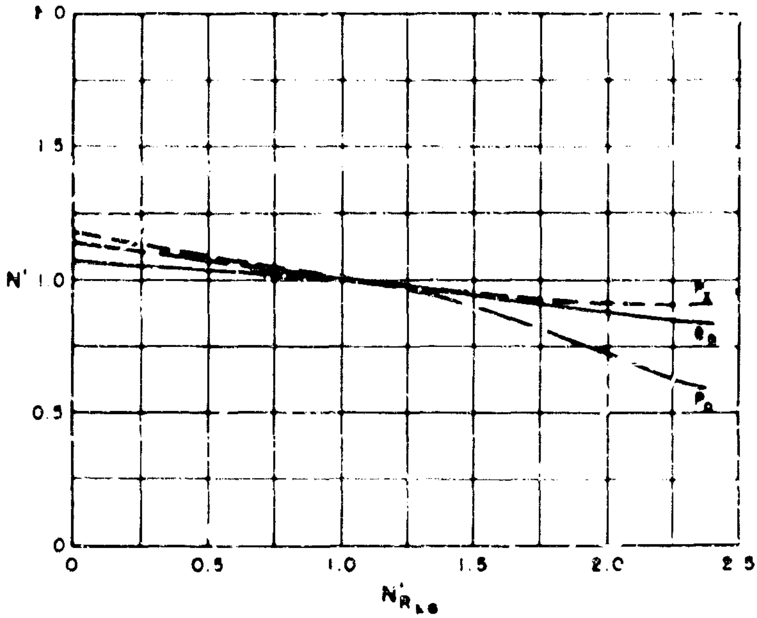


FIG. 51—NORMALIZED PERFORMANCE VS. GROUNDED GRID-CATHODE BIAS RESISTANCE FOR THE CATHODE COUPLED OSCILLATOR
10 - 150 MC



CAPACITY COUPLED

FIG. 52—NORMALIZED PERFORMANCE VS. GROUNDED GRID-CATHODE BIAS RESISTANCE FOR THE CATHODE COUPLED OSCILLATOR
10-150 MC

Fig. 52

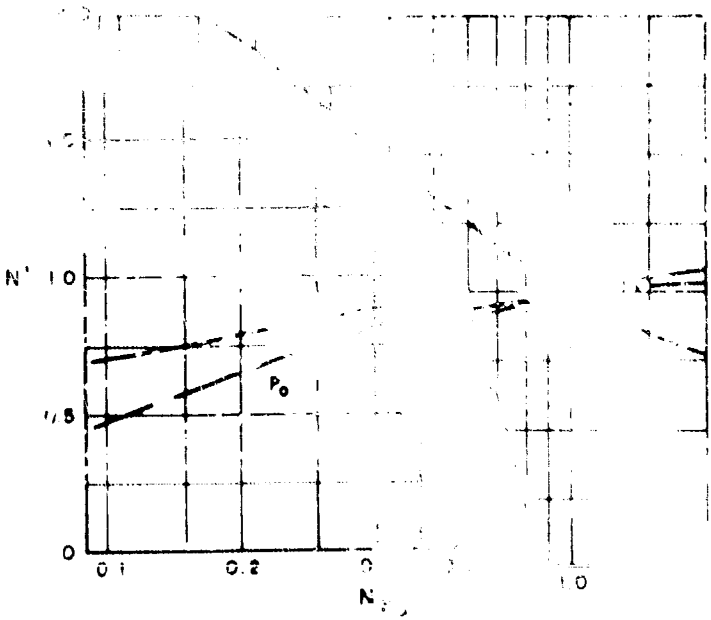
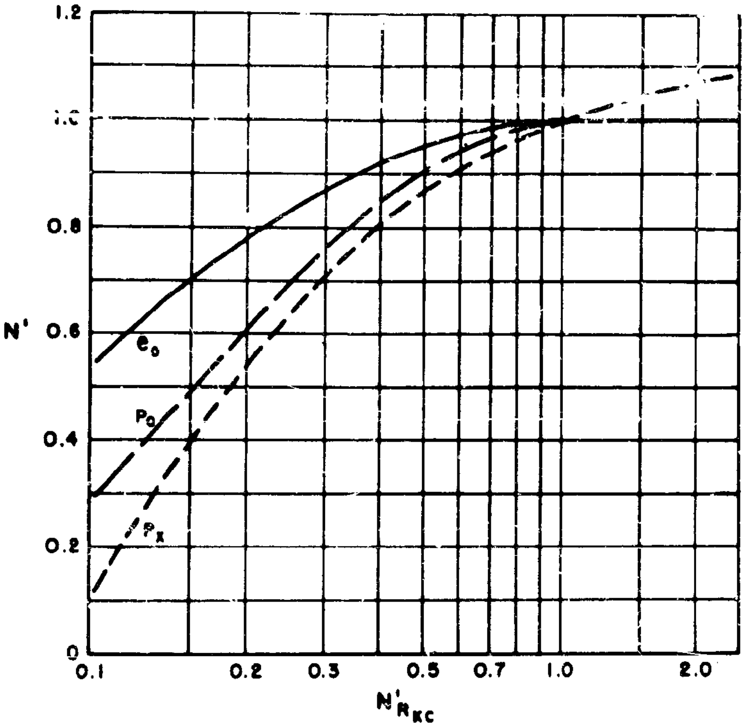


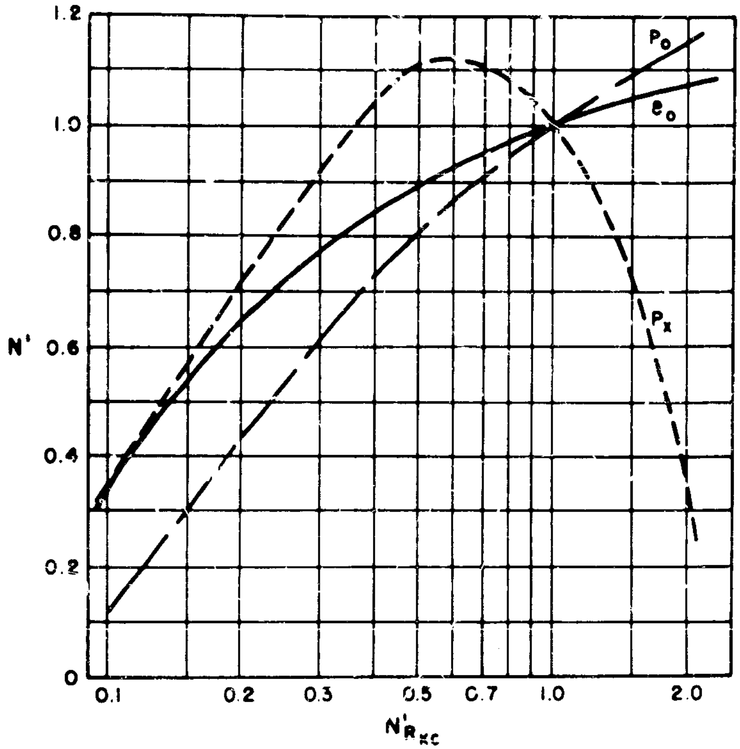
FIG. 33—NORMALIZED PERFO... FOLLOWER - GRID BI... THE CATHODE COUPL... 10-15...



DC COUPLED

FIG. 54 — NORMALIZED PERFORMANCE VS. CATHODE FOLLOWER – CATHODE BIAS RESISTANCE FOR THE CATHODE COUPLED OSCILLATOR 10–150 MC

Fig. 54



CAPACITY COUPLED

FIG. 55 — NORMALIZED PERFORMANCE VS. CATHODE FOLLOWER – CATHODE BIAS RESISTANCE FOR THE CATHODE COUPLED OSCILLATOR
10 – 150 MC

Fig. 55

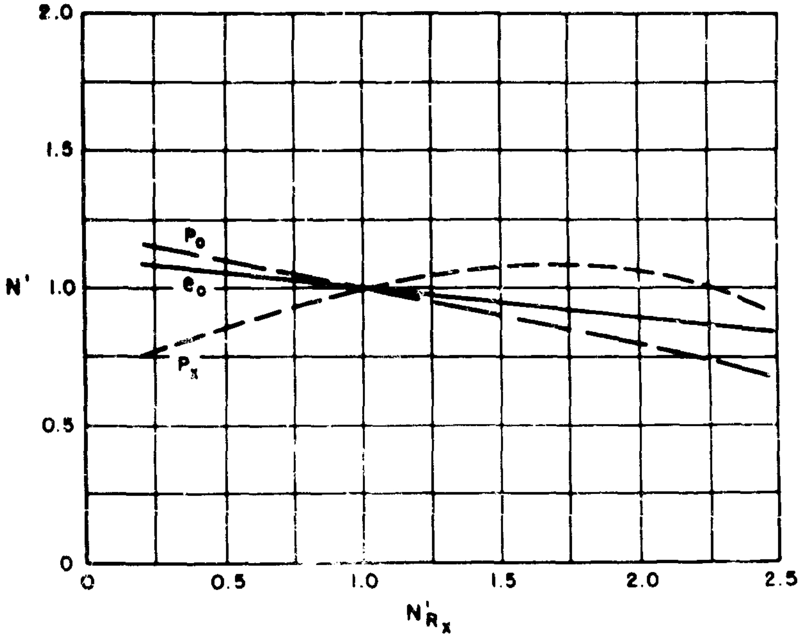


FIG. 56— NORMALIZED PERFORMANCE VS. CRYSTAL RESISTANCE FOR THE CATHODE COUPLED OSCILLATOR

10 – 150 MC

Fig. 56

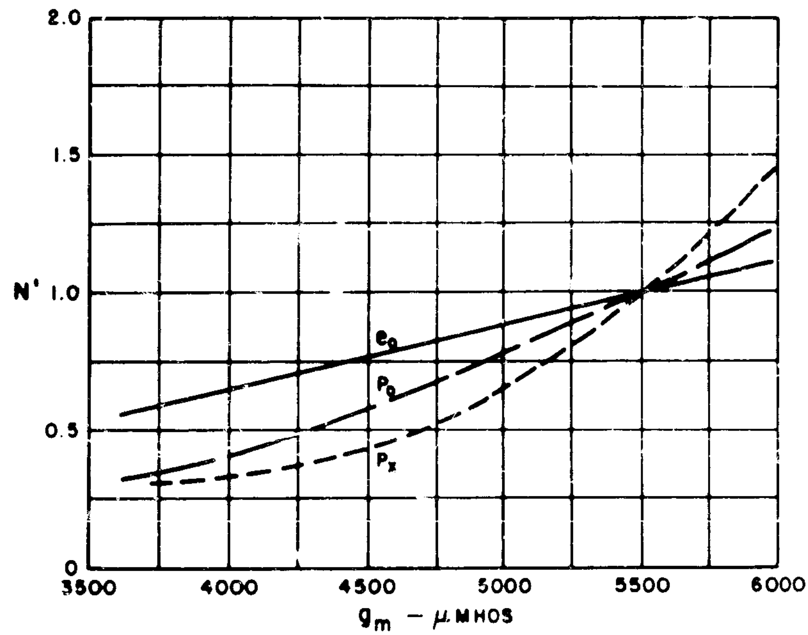


FIG. 57—NORMALIZED PERFORMANCE WITH VARIATION IN TUBE TRANSCONDUCTANCE FOR THE CATHODE COUPLED OSCILLATOR 10-150 MC

Fig. 57

PART B

ANTIRESONANT CRYSTAL OSCILLATOR CIRCUITS

COLPITTS

ELECTRON COUPLED COLPITTS

MILLER

0.8 - 5.0 mc

3.0 - 20 mc

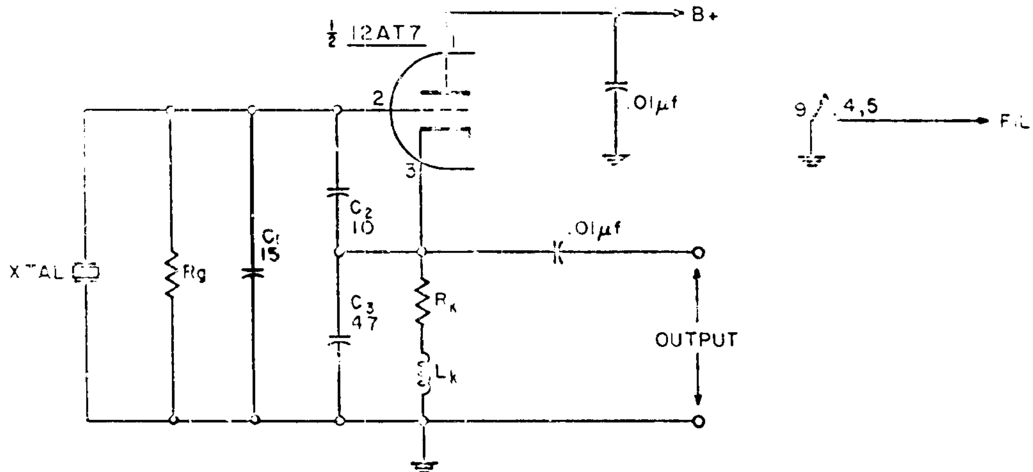
1. COLPITTS (GROUNDED PLATE PIERCE) OSCILLATOR CIRCUIT - 0.8-20.0 mc

The Colpitts, or Grounded Plate Pierce, antiresonant oscillator consists of a single triode amplifier stage. The plate is ac grounded and the output is developed across the cathode-to-ground circuit, which is composed of an inductance and a bias resistor. Feedback is accomplished by the capacitance from cathode to grid. The crystal is connected between grid and ground; grid bias is developed with the grid-to-ground resistance and the crystal load capacitance. Capacitance across the crystal, together with that of the voltage divider, provides the required capacitive load for the crystal. For MilSpec crystal units, this value is specified as either 20 or 32 mmfd. The most common value is 32 mmfd and is the one used in the circuit described below. The antiresonant tank circuit is composed of this load capacitance and the equivalent inductance of the crystal.

a Circuit Description

The circuit diagram of the Colpitts oscillator recommended for operation in the 0.8 to 20.0 mc frequency range is shown in Fig. 58. The only physical coil in the circuit is L_k, for which nominal values are shown in the figure. The values of C_1, C_2, and C_3 designate physical capacitors. The method of determining these values is outlined below in the subsection on "Initial Circuit Alignment Procedure."

The reference oscillator circuit, to which all performance and design data is compared, uses one section of a 12AT7 miniature dual triode tube with a nominal g_m of 5500 µmhos. All resistance, bypass, and decoupling component values are shown in Fig. 58. The load resistance is 10K ohms. C_1 is 21.25 mmfd (15 mmfd + strays), C_2 is 12.00 mmfd (10 mmfd + strays) and C_3 is 74.50 mmfd (47 mmfd + 15 mmfd circuit load capacitance + strays).



R IN OHMS
C IN μμf
L IN mh
UNLESS OTHERWISE SPECIFIED

f MC	Rg OHMS	R_k OHMS	L_k mh
0.8-5.0	1M	3.9K	10
3.0-20.0	100K	330	0.5

FIG.58 —COLPITTS OSCILLATOR
0.8 - 20.0 MC

These values yield the ratios $C_1/C_t = 21.25/32 = 0.66$ and $C_3/C_2 = 74.50/12 = 6.2$.

b. Component and Circuit Construction Details

The general component types used in this circuit are described in the first and third paragraphs of Part A.1.b. The effects of lead dress and stray circuit capacitances are not as important here as they are at the higher frequencies, except as they effect the values of the grid circuit load capacity combination. However, good engineering practices in circuit construction should be followed.

c. Initial Circuit Alignment Procedure

This circuit does not involve tuning as normally considered, but does require adjustment of the circuit capacitances to provide proper values of crystal load capacitance and feedback ratio. Once this is done, the frequency can be changed simply by switching in the proper crystal which will then oscillate at its fundamental frequency. The ratio of C_3 to C_2 used in the recommended circuit is 6.2. The test equipment required is a Boonton Radio Corporation Q Meter, Model 160A, or equivalent means of capacity measurement. The procedure follows:

1. Select a frequency for measurement at the approximate mid-frequency band of the oscillator.
2. Connect rigidly supported clips to the capacitor terminals of the Q Meter.
3. Select an inductor that will resonate with approximately 100 mmfd at the frequency setting of Step 1, and place in the coil terminals of the Meter.
4. Attach one of the clips to the grounded side of the crystal socket. Make sure the crystal is removed from the socket. Place the other

clip near, but not touching, the other crystal socket terminal.

5. Short C_3 (cathode to ground) with a short piece of wire.

6. Turn on Meter and adjust the main capacitor dial for a peak meter reading. This must be done with accuracy. Note the capacitance dial reading.

7. Attach the free clip lead to the crystal socket terminal and repeak the meter reading. Note reading of the capacitance dial. The difference between the two readings is ΔC_a.

8. Repeat the procedure with C_2 shorted. This capacitance difference is ΔC_b.

9. Place Meter leads from cathode-to-ground. Repeat the procedure with C_1 shorted. The resulting capacitance difference is ΔC_c.

10. Substitute the difference readings into the following formulae to obtain the desired capacitance values.

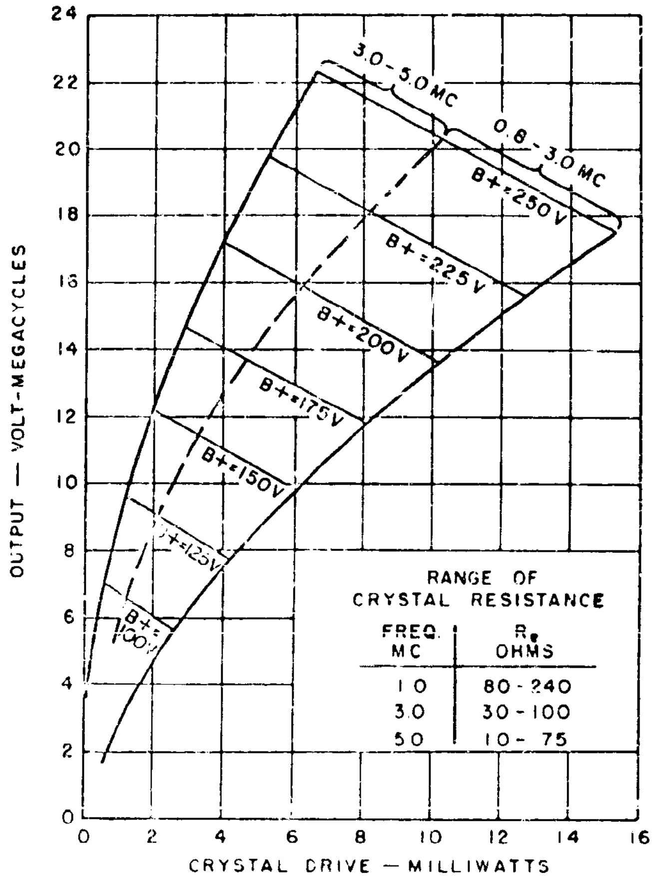
$$C_1 = (\Delta C_a - \Delta C_c + \Delta C_b)/2$$
$$C_2 = (\Delta C_a - \Delta C_b + \Delta C_c)/2$$
$$C_3 = (\Delta C_c - \Delta C_a + \Delta C_b)/2$$

11. The individual circuit capacitances may now be adjusted by adding or substracting known capacitance values.

12. The value of load capacitance, may be found by simply measuring the grid-to-ground capacitance with crystal removed and no shorting wires present.

d. Circuit Performance Characteristics

Performance curves for the Colpitts oscillator in the ranges 0.8 to 5.0 and 3.0 to 20.0 mc are shown in Figs. 59 and 60, respectively. Oscillator output is given in volt-megacycles (product of rms voltage and frequency in megacycles). The range of equivalent antiresonant crystal



FREQ. MC	R_e OHMS
1.0	80-240
3.0	30-100
5.0	10-75

FIG. 59 — PERFORMANCE CHARACTERISTICS OF THE COLPITTS OSCILLATOR 0.8-5.0 MC

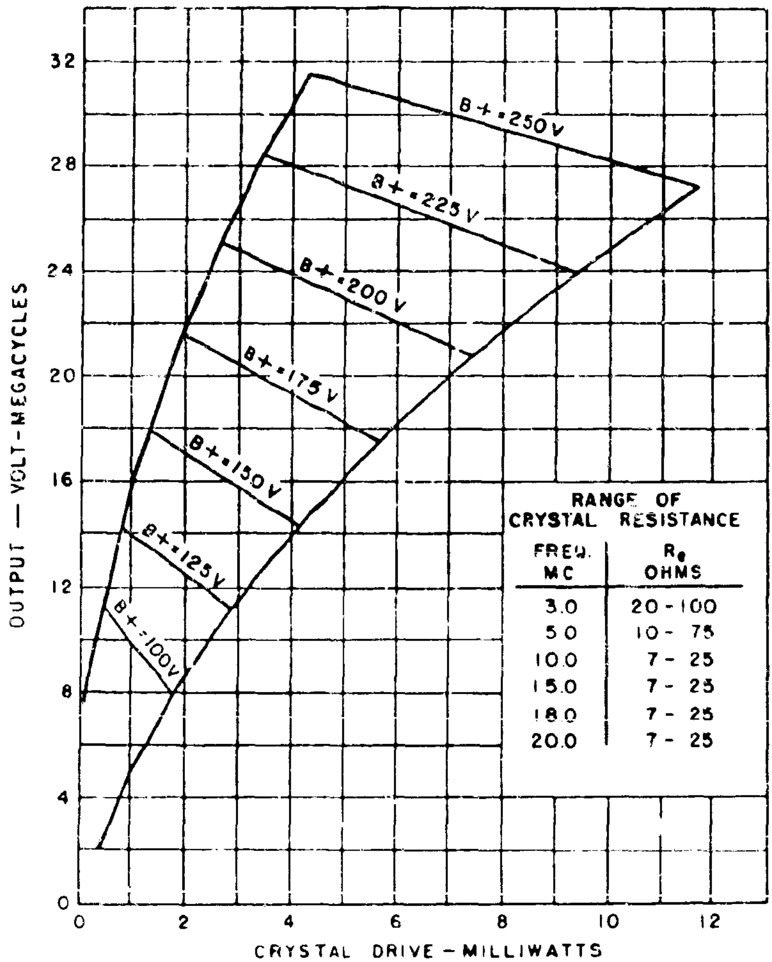


FIG. 60 —— PERFORMANCE CHARACTERISTICS OF THE COLPITTS OSCILLATOR 3 – 20 MC

resistances, R_e, is shown in each figure. Oscillator performance at 10 mc as a function of R_g, R_K, R_L, C_1/C_t, C_3/C_2, and tube type is shown in Figs. 61 through 66 respectively.

Application of these curves to oscillator circuit design is shown in the subsection below.

e. Circuit Design Examples and Use of Curves

The Colpitts oscillator circuit shown in Fig. 58 is designed to operate over the frequency range of 0.8 to 20.0 mc with the indicated component values and provides large output voltage to crystal drive ratios. The performance characteristics shown in Figs. 59 and 60 can be used directly in predicting operation of the circuit and, together with the other performance curves, can be used to design additional Colpitts circuits meeting specific performance requirements.

An example of the use of these curves is shown here. Assume an oscillator is required to operate at 7.0 mc and have an output of 2.25 volts rms across a load of 5000 ohms. The available power supply will provide 150 volts at 30 ma. The crystal should be selected from the preferred types whose specifications are given in MIL-C-3098B. Of the available units, the CR-18/U, CR-27/U, and the CR-36/U cover this frequency range. Other characteristics of the crystal should be kept in mind, namely, recommended maximum crystal drive level (ten milliwatts for the type used here), effective resistance, etc.

The first step toward the actual design of the oscillator is the computation of the volt-megacycle product. In this example, the product is 2.25 x 7 = 15.75. Referring to Fig. 60, draw a horizontal line from 15.75 on the volt-megacycle scale. This line intersects the B+ = 150 volt line at a drive level of 3.0 mw, obtained by projecting a vertical line from the

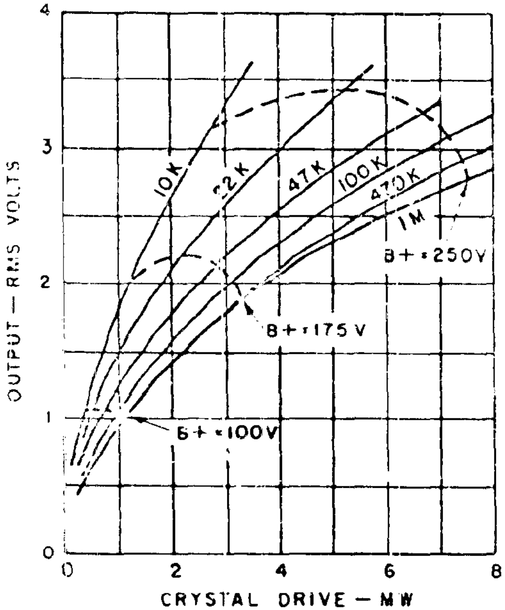


FIG.61 —— COLPITTS OSCILLATOR PERFORMANCE AS A FUNCTION OF R_G AT 10 MC

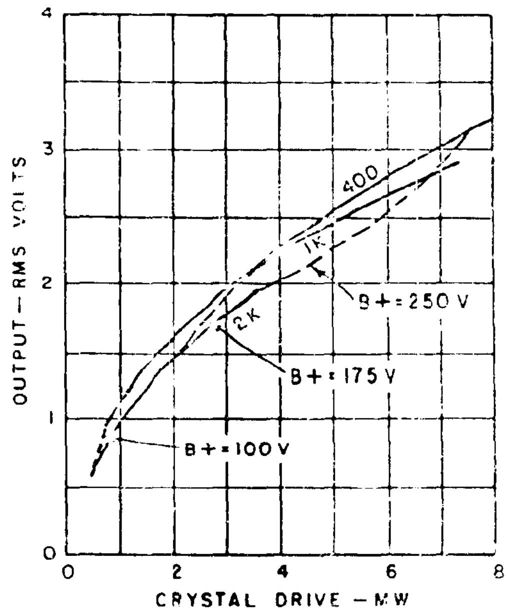


FIG.62 —— COLPITTS OSCILLATOR PERFORMANCE AS A FUNCTION OF R_K AT 10 MC

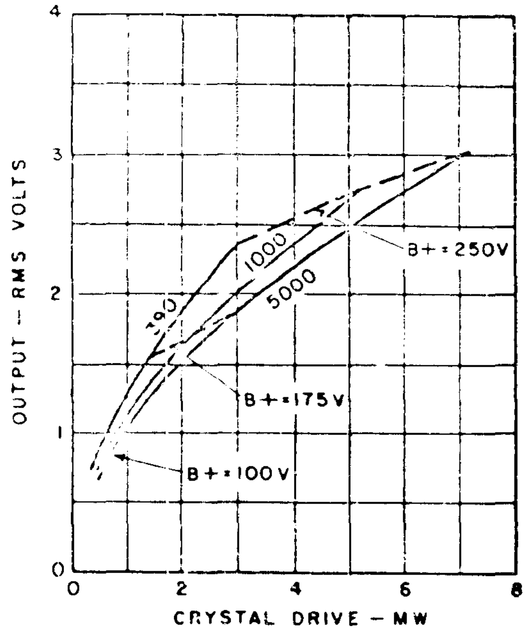


FIG.63 — COLPITTS OSCILLATOR PERFORMANCE AS A FUNCTION OF R_L AT 10 MC

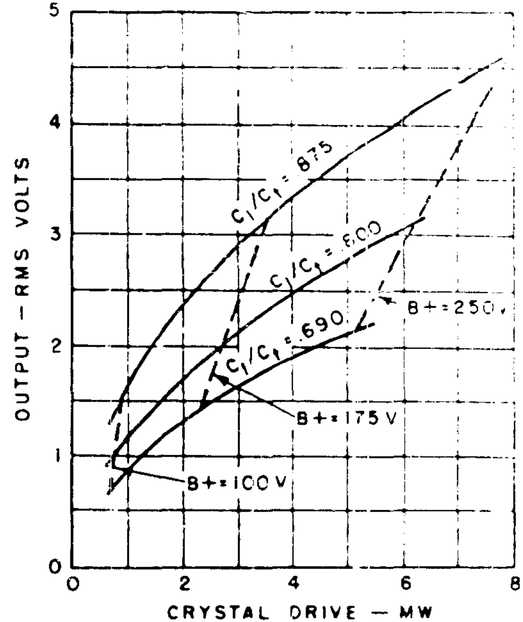


FIG. 64 — COLPITTS OSCILLATOR PERFORMANCE AS A FUNCTION OF C_1/C_t AT 10 MC

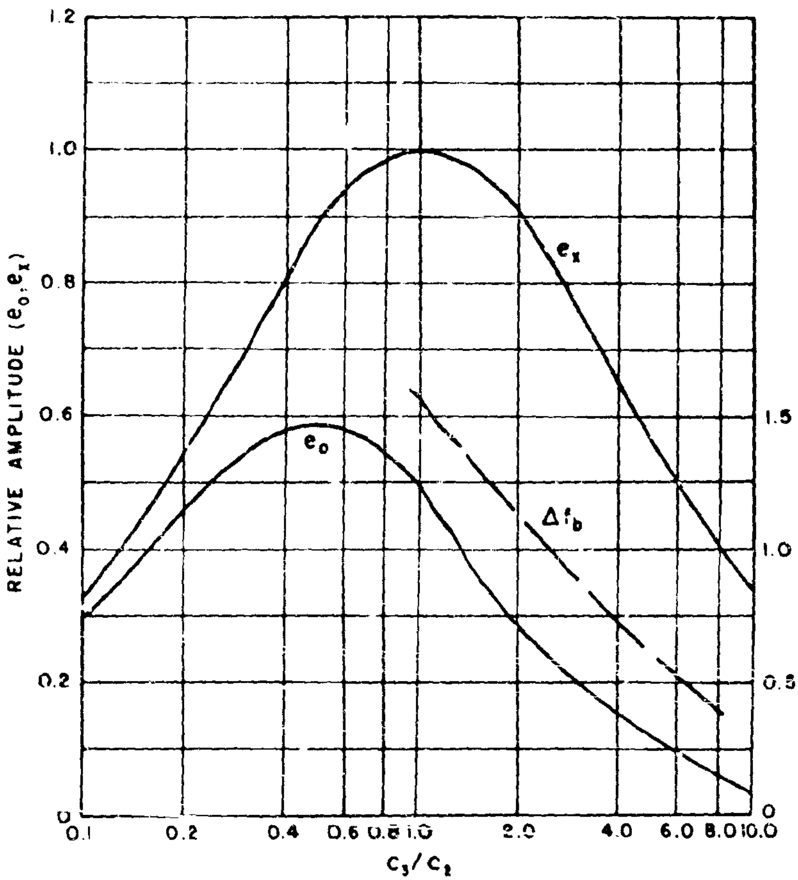


FIG. 65 —— CIRCUIT PERFORMANCE VS. CAPACITY RATIO C_3/C_2 FOR THE COLPITTS OSCILLATOR

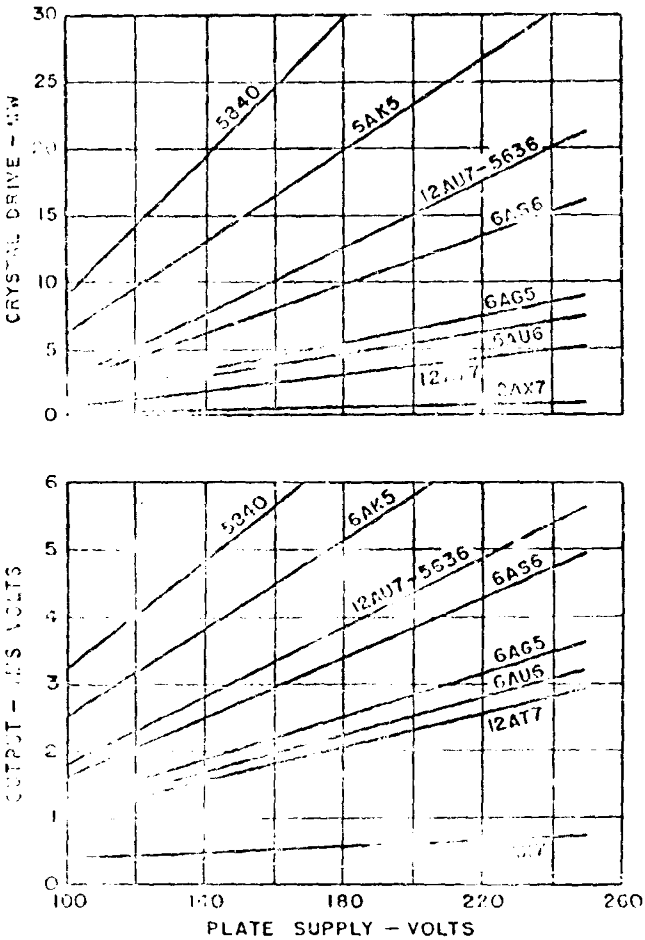


FIG.66 —— COLPITTS OSCILLATOR OUTPUT AND CRYSTAL DRIVE FOR VARIOUS TUBE TYPES.

intersection down to the crystal drive scale. By drawing similar verticals from the ends of the 150 volt line horizontally and vertically, the range of outputs and crystal drives may be obtained for varying values of antiresonant crystal resistances. For the case of 7.0 mc, the output ranges from about 2.0 to 2.6 volts and the corresponding drive levels from 1.3 to 4.2 mw. The reference circuit meets these specifications when operated at a plate supply voltage of 150 volts.

Circuit performance with the use of other tube types or changes in component values can be determined from the use of Figs. 61 through 66. These modifications may be necessary when the desired output cannot be obtained with the reference circuit, or when another tube type is preferred due to size or power considerations. The design method may also be used when the oscillator requirements fall outside the performance of the reference circuit. The following is an example illustrating the use of this method.

Assume that this same circuit, operating at 7.0 mc, is to have an output of 2.8 volts across a 5000 ohm load. The power supply again provides 150 volts at 30 ma. The new volt-megacycle product is 2.8 x 7.0 = 19.6. The plate voltage required for the reference circuit is approximately 175 volts, from Fig. 60. Therefore, the circuit parameters must be modified to conform with the available power supply voltage. Several methods will be indicated.

The design curves of Figs. 61 through 66 indicated performance of the reference circuit at a frequency of ten megacycles with changes in circuit parameters. However, the percentage change in performance with variations in circuit component or parameter value is approximately the same for all frequencies in the 0.8 to 20.0 mc range. Therefore, these curves may be used at the desired design frequency, keeping in mind that the resulting voltages and drive levels derived from these curves are relative values only, and must always be referenced to the original curves (Figs. 59 and 60) for the final performance value.

The desired prerformance in the design example may be obtained by using a different tube type. Figure 66 shows the output and crystal drive characteristics obtained with a number of tube types. Construct a horizontal line passing through the intersection of the 12AT7 output voltage curve and the 175 volt plate supply point. This yields a relative output of 2.0 volts. Intersections of this line with the various tube output curves show that the same output may be obtained with a 12AU7 or 5636 at 108 volts, a 6AS6 at 115 volts, a 6AQ5 at 148 volts, or a 6AU6 at 162 volts. The pentodes are triode-connected for use in this circuit. The output requirements could be met by a 5840 or a 6AK5 operating at less than 100 volts, the exact voltage being obtained by extrapolating the proper curve. Assume the selection of the 5636, operating at 108 volts. The relative drive at this voltage, obtained from the upper graph of Fig. 66, is 4.0 mw.

If the 150 volt supply is used, a higher relative output (3.1 volts) and drive level (8.5 mw) is indicated. If the actual output is to remain fixed at 2.8 volts, the 5636 may be used at a B+ of 150 volts if various circuit modifications are made. This can be accomplished by changing the bias resistances, load resistance, the capacitive ratio C_3/C_2, or C_1.

Generally, it is not desirable to vary the bias resistance values. The recommended circuit values should be used where possible. However, Fig. 61 shows that for operation at ten megacycles, increasing the value of R_g decreases output, but increases the drive level. In addition, since this component varies approximately inversely with frequency, a higher value of R_g would be required at 7.0 mc. Unfortunately, for the purpose of the design example used here, at the required value of plate supply voltage, the output could only be reduced at the expense of an excessive increase in crystal drive level. Inspection of Fig. 62 shows that this is also true of changes in R_k.

At a fixed B+ voltage, decreases in the load resistance will decrease output and drive. Examination of Fig. 63 shows that the desired reduction of the output voltage may be obtained by reducing the load resistance from the reference value of 10,000 ohms to two or three thousand ohms. However, the design requirements call for a load of 5000 ohms. If this is to be maintained, another method of reducing output must be investigated.

The capacitance ratio, C_3/C_2, can be changed to obtain the desired results. Effects on performance of this parameter are shown in Fig. 65. Drew a horizontal line through the intersection of the output voltage curve and the recommended value of $C_3/C_2 = 6.2$. This shows a relative output amplitude of 0.09 on the left scale. From Fig. 66 it is determined that a circuit using the 5636 tube will have a relative output of 2.0 volts at a B+ of 108 volts, and this output will increase to 3.1 volts (or by a factor of 1.55) when the plate supply voltage is increased to 150 volts (the required value). To obtain the desired output at 150 volts, the relative amplitude of Fig. 65 must be decreased by this factor, or 0.09/1.55 = 0.058. For this relative amplitude, the required capacity ratio is approximately 8.0. To determine the actual values of capacity required to obtain this ratio, the following procedure applies.

The ratio $C_3/C_2 = 8.0$ and the value of $C_t = 32$ mmfd must be kept constant for these crystal units. By keeping the combined capacitance of

C_2 and C_3 at the recommended value of 10.75 mmfd $(= \frac{C_2C_3}{C_2 + C_3})$, C_1 need not be changed. Therefore, solution of the following equations will provide the new values for these two capacitors.

$$C_3/C_2 = 8.0$$

$$\frac{C_2C_3}{C_2 + C_3} = \frac{C_3}{1 + C_3/C_2} = 10.75$$

Therefore, solution shows that C_2 = 12.1 mmfd and C_3 = 96.8 mmfd. With these values of capacity and a 5636 tube operating at 150 volts B+, the circuit will have an output of 2.8 volts rms at a drive originally determined from Fig. 66, in the range of 2.0 to 5.8 mm to yield good stability.

Where low drive level is a major consideration, reducing the output voltage by the previously described techniques will reduce the power dissipated in the crystal. For best frequency stability a crystal unit should not be operated at a minimum drive level, i.e., where the oscillations are on the verge of becoming erratic. This value is below a few tenths of a milliwatt for typical antiresonant units.

f. Additional Performance Characteristics

Several other oscillator performance characteristics have been determined and are presented here. Stability characteristics of the Colpitts oscillator operating at ten megacycles are given and are typical for the entire frequency range of interest. No appreciable change in frequency can be noticed for a ±10 percent change in the filament voltage. However, values of Δf_b range from 0.5 to 1.0 ppm for ±10 percent change in B+, over a plate supply voltage range of 100 to 250 volts. The effects of C_3/C_2 on Δf_b are shown in Fig. 65.

Crystal unit specifications for this frequency range call for a maximum deviation from the nominal crystal frequency of 50 ppm throughout the temperature range of -55°C to +90°C. Changes from the mean frequency encountered for typical units are about 15 ppm. Circuit temperature-frequency variations, due to temperature coefficients of the component parts, account for some 20 ppm, and when combined with the maximum crystal unit deviation, totals less than 70 ppm. By including the effects of B+ and filament voltage variations, the maximum deviation in frequency is raised to about 75 ppm. However, under typical operating conditions, this figure is less than 40 ppm. Crystal and circuit frequency changes for typical operation at 10 mc are shown in Fig. 67.

The actual operating frequency with respect to the antiresonant frequency of the crystal unit is dependent on the crystal load capacity. For typical, commercially available capacitors, the circuit will operate within five to ten parts per million of the antiresonant frequency.

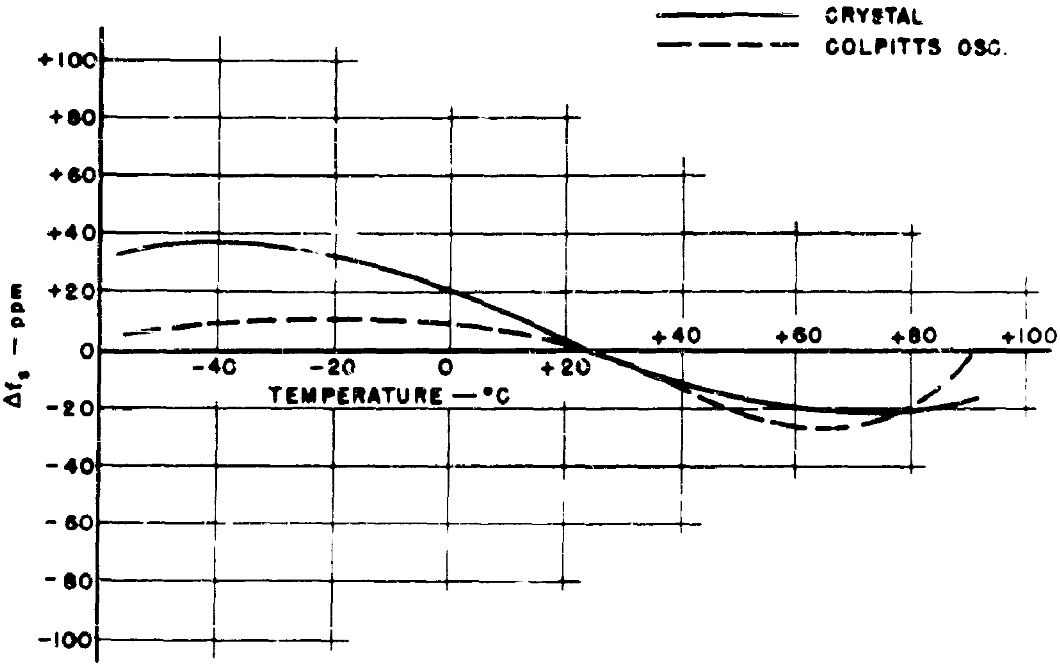


FIG. 67 — FREQUENCY TEMPERATURE CHARACTERISTICS
R_x = 20 Ω, f = 10 mc
CRYSTAL #164

2. ELECTRON COUPLED COLPITTS OSCILLATOR CIRCUIT - 0.8-20.0 mc

The Electron Coupled Colpitts antiresonant oscillator consists of a single pentode stage. The screen grid acts as the oscillator anode and the output is obtained from a tuned coil in the plate circuit, effectively isolating the oscillator portion of the circuit from changes in the load circuit. In all other respects, this circuit is the same as that of the Colpitts oscillator discussed in Part B.1.

a. Circuit Description

The circuit diagram of the Electron Coupled Colpitts oscillator operating in the 0.8 to 20 mc frequency range is shown in Fig. 68. Besides L_k, values for which are indicated in the figure, the other coil required is L_p, the plate tank inductance. Generally this coil is fixed tuned to the desired frequency in combination with a variable capacitor in the plate circuit. The coil may be made to resonate with the stray plate circuit capacitances; however, the size and Q of such a coil might be prohibitive. The values of C_1, C_2, and C_3 may be determined from the discussion on "Initial Circuit Alignment Procedure," Part B.1.a.

The recommended oscillator circuit uses a 6AG6 miniature pentode tube with a nominal g_m of 5000 μmhos. The load resistance is taken as 100K ohms. All other resistance, bypass, and decoupling component values are shown in Fig. 68.

b. Component and Circuit Construction Details

The general component types used in this circuit are described in the first and third paragraphs of Part A.1.b. and Part B.1.c. The tube socket is of the miniature seven pin phenolic type, with shield base.

R IN OHMS
C IN $\mu\mu f$
L IN mh
UNLESS OTHERWISE SPECIFIED

	R_x OHMS	L_x mh
	3.9K	10
	330	0.5

FIG.68 —ELECTRON COUPLED COL[illegible] [illegible]TOR
0.8 - 20.0

c. Circuit Tuning Procedure

The only elements which are adjusted during circuit operation are the plate tank circuit components. The circuit is adjusted for peak output by tuning L_p or C_p, whichever is variable.

d. Circuit Performance Characteristics

Performance curves for the Electron Coupled Colpitts oscillator operating in the ranges 0.8 to 5.0 mc and 3.0 to 20.0 mc are shown in Figs. 69 and 70, respectively. The performance due to component changes effected in this circuit will follow the trends shown for the Colpitts oscillator, described in Part B.1.d. and e.

e. Circuit Design Considerations

Specific design examples for the Electron Coupled Colpitts oscillator are not given here, since this is essentially an extension of the design procedures discussed in Part B.1.e. on the Colpitts oscillator. Certain characteristics of the Electron Coupled Colpitts oscillator must be mentioned, however.

In order to assure the independence of the oscillator operation from plate voltage variations, the plate supply voltage should be made somewhat larger than the screen voltage. The difference between these two voltages should be larger than the peak swing of the ac output signal in order to insure th the instantaneous plate voltage is always positive with respect to the screen voltage.

In addition, greater isolation and frequency stability of the circuit may be obtained by connecting the suppressor to a positive bias source, the value of which should be approximately equal to the dc cathode voltage.

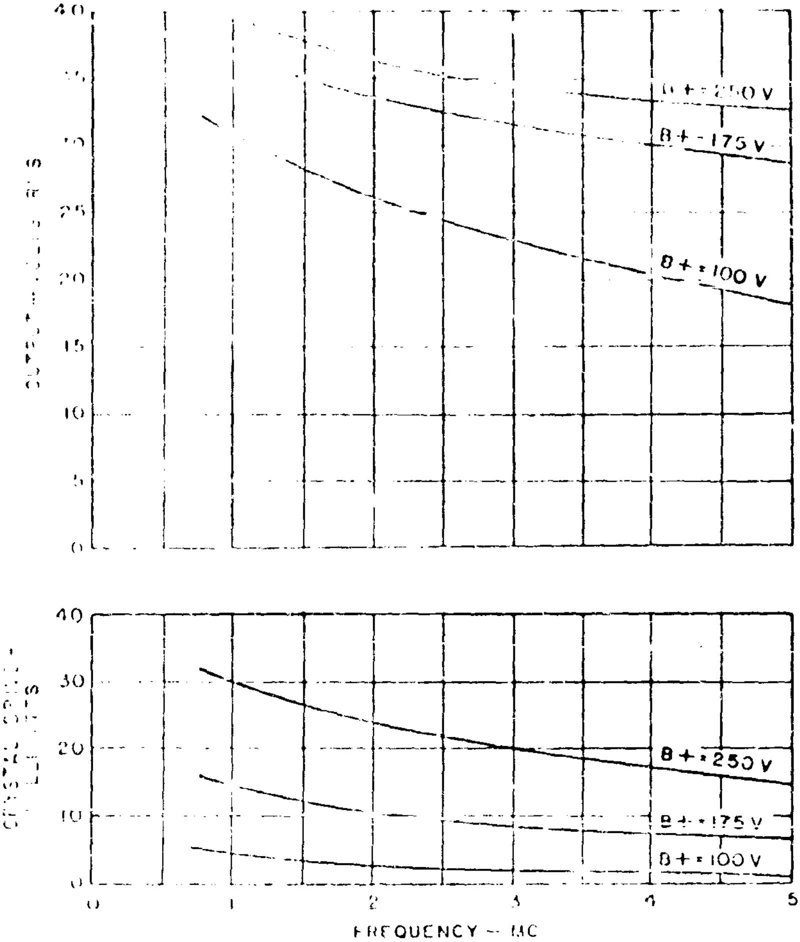


FIG. 69 PERFORMANCE CHARACTERISTICS OF THE ELECTRON COUPLED COLPITTS OSCILLATOR 0.8 - 5.0 MC

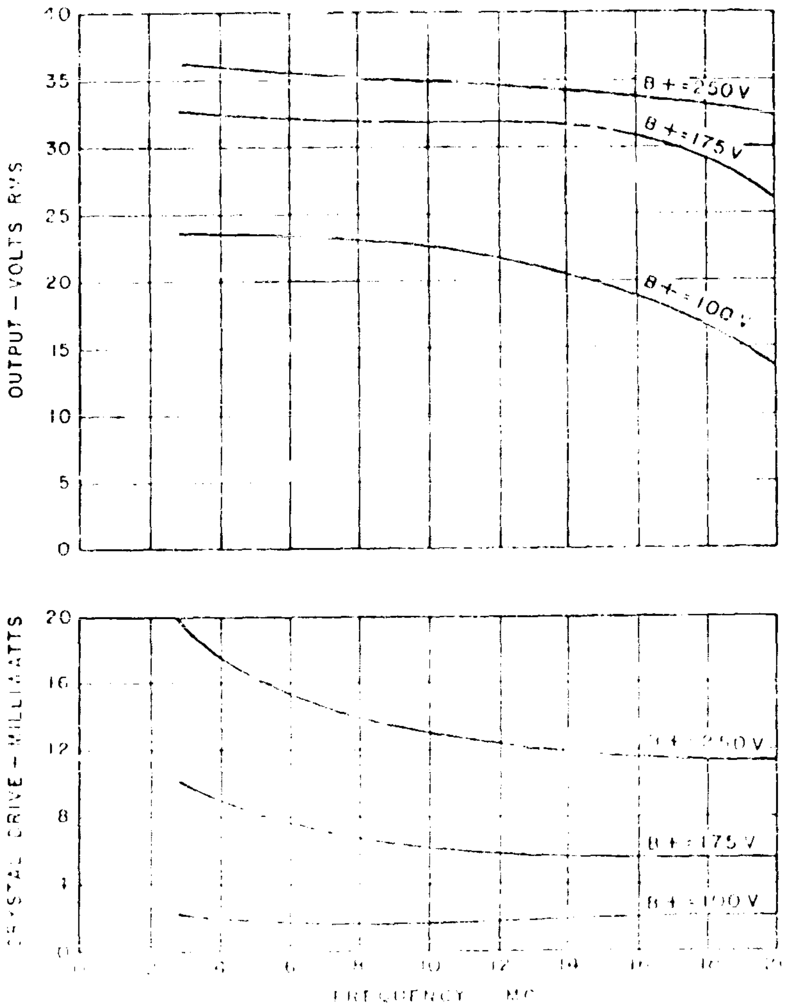


FIG. 72 PERFORMANCE CHARACTERISTICS OF THE ELECTRON COUPLED COLPITTS OSCILLATOR [illegible]

As the plate circuit is tuned through resonance, the available output voltage is greater by about 30 percent, when the suppressor grid is tied to the plate, rather than to a positive bias source. However, for frequency change with change in tuning, the plate connection results in a frequency change of about 20 ppm, while the bias connection results in changes of only two or three parts per million.

f. Additional Performance Characteristics

Frequency stability of the Electron Coupled Colpitts oscillator with changes in plate supply voltage is quite good, averaging less than 0.8 ppm throughout the 100 to 250 volt B+ range. Frequency stability figures with changes in filament supply voltage are on the order of a few tenths of a part per million.

Frequency stability with changes in temperature are comparable to the figures obtained for Colpitts oscillator, discussed in Part B.1.f.

3. THE MILLER OSCILLATOR CIRCUIT - 0.8-20.0 MC

The Miller oscillator consists of a triode or pentode amplifier stage, where feedback is accomplished through the plate-to-grid capacitance. In the case of pentode operation, this capacitance is small and usually necessitates the addition of physical capacity for sufficient feedback. The required 20 or 32 mmfd crystal load capacitance for typical military crystal units, is composed of the grid-to-ground capacitance and the effects of the plate-to-grid capacitance. The plate-to-grid capacitance is a function of the gain of the tube because of the well known Miller effect. The proper circuit phase condition for oscillations and best frequency correlation and stability occur when the plate circui tuning element is tuned to provide 70 percent of peak output by decreasing capacitance or inductance so the resultant plate impedance is inductive.

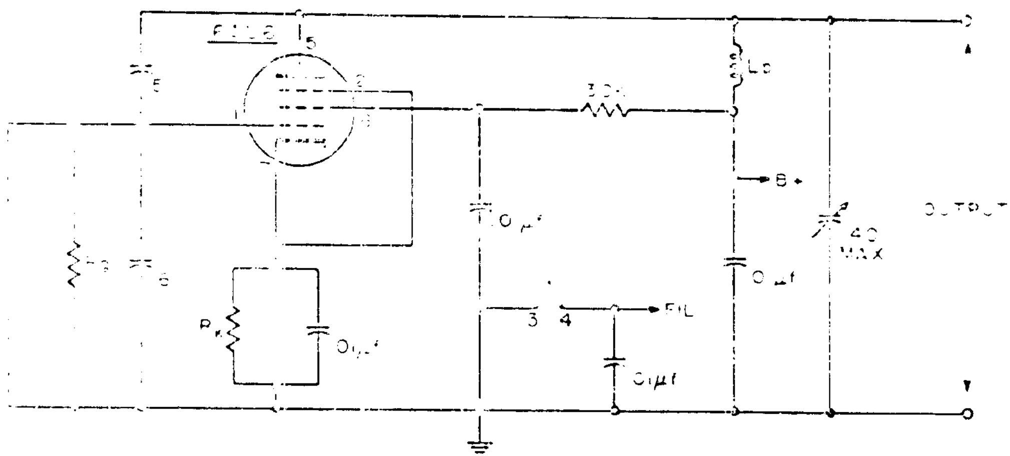
a. Circuit Description

The circuit diagram of the Miller oscillator investigated for use in the 0.8 to 20.0 mc frequency range is shown in Fig. 71. The use of a pentode in this circuit requires the addition of about five mmfd, to the grid-to-plate capacitance for proper operation.

The recommended circuit uses a 6AU6 miniature pentode with a nominal transconductance of 5000 μmhos. The load resistance is taken as 100,000 ohms. Bypass and decoupling component values are as shown in Fig. 71. The plate tuning element may be an inductor, however, because of the physical sizes involved, it is advisable to use a fixed inductance shunted by a variable capacitor.

b. Component and Circuit Construction Details

General comments on component selection and circuit construction



UNLESS OTHERWISE SPECIFIED

f MC	Rg OHMS	Rk OHMS
0.8-5.0	1M	3.9K
3.0-20.0	100K	330

FIG. 71 --MILLER OSCILLATOR
0.8 - 20.0 MC

practices are contained in the first and third paragraphs of Part A.1.b. and in Part B.1.b.

c. Initial Circuit Adjustment and Tuning Procedure

The basic adjustment of the circuit consists of obtaining the required crystal load capacitance. The stray capacitance from grid to ground is about 6 mmfd for typical construction. This is padded by the addition of 16 mmfd to a total capacitance of about 22 mmfd. The plate-to-grid capacitance is small and must be padded to obtain the required result. With a grid-to-plate gain of two which is typical for this circuit, this capacitance must total five mmfd, and the crystal load will then be the necessary value of 32 mmfd. For more accurate determination of the capacitive load, another method is used. The crystal is tested in a standard Crystal Impedance meter with the proper capacitive load and the frequency is noted. When placed in the Miller circuit, the capacities are adjusted to obtain the same frequency under the recommended tuning conditions.

Tuning of the circuit consists of adjusting the plate impedance for an output of 70 percent of the peak reading, on the inductive side of tuning.

d. Circuit Performance Characteristics

Curves of output and crystal drive versus frequency of operation for the ranges 0.8-5.0 mc and 3.0-20.0 mc are shown in Figs. 72 and 73. These graphs depict performance of a circuit having the component and circuit parameter values indicated in Fig. 71. Design information on this circuit is not given, since extensive investigation of the oscillator has not been made. However, some performance characteristics may be discussed. Certain circuit parameters of the Miller oscillator have effects on performance similar to those of the Colpitts oscillator. These include the values of R_x, R_g, and

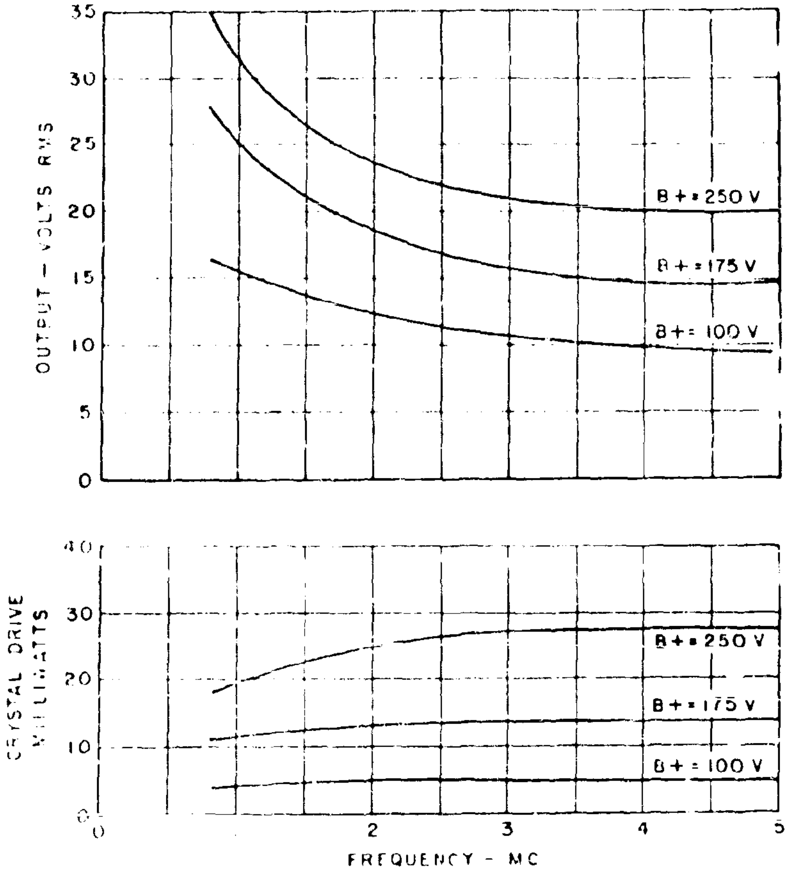
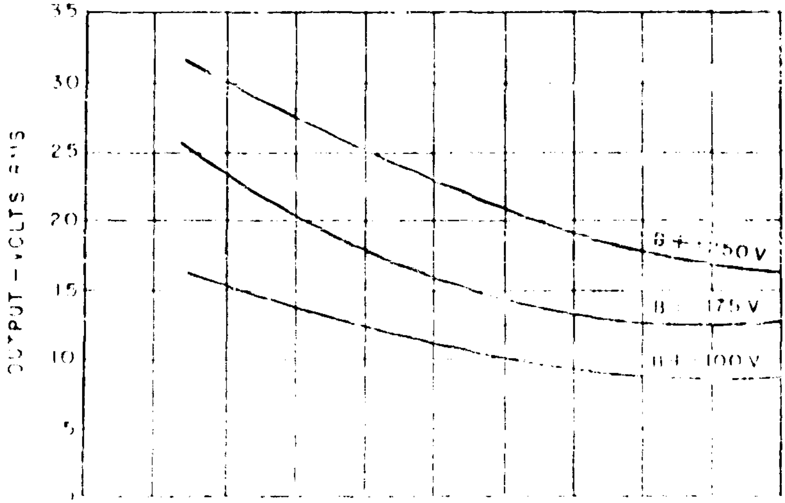


FIG 72 —— PERFORMANCE CHARACTERISTICS OF THE MILLER OSCILLATOR 0.8 - 5.0 MC


35
30
25
20
15
10
5
175 V
100 V

R_L. A review of Part B.1.e. specifically those paragraphs referring to circuit component variations, should be made.

The stability of the circuit with ±10 percent changes in the B+ voltage averages less than a part per million over the range of plate supply voltages used, and is typical for the frequency range. Correlation figures, however, depend on the value of the crystal load capacitance and may vary according to the accuracy with which this parameter is selected. Frequency-temperature variations are comparable to those discussed for the Colpitts oscillator in Part B.1.f.

APPENDIX

II

REFERENCES

REFERENCES

1. Gruen, H. E., "Development of a Design Technique for Antiresonant Crystal Oscillators", Final Report, Contract No. AF 33(616)-2125, Call No. 12, Armour Research Foundation, 25 October 1955, or see Electronics, Vol. 30, No. 1, pp 146-150, January, 1957.

2. Edson, W. A., et al, "High Frequency Crystal-Controlled Oscillator Circuits", Final Report, Contract No. W36-039-sc-36841, Georgia Institute of Technology, December, 1950.

3. Mason, W. P. and Fair, I. E., " A New Direct Crystal-Controlled Oscillator for Ultra-Short Wave Frequencies", Proc. IRE, Vol. 30, pp 464-472, 1942.

4. Davies, G. L., et al, Progress Reports on Naval Research Laboratories Contract No. Nonr-643(00), G. L. Davies Laboratories

5. Lister, G. H., "Overtone Crystal Oscillator Design", Electronics, Vol. 23, No. 11, pp 88-93, November, 1950.

6. Heegner, K., "Gekoppelte Selbsterregte Elektrische Kreise und Kristelloszillatoren", E.N.T., Vol. 15, p 364, 1938.

7. Guttwein, G. K., "Extension of the Upper Frequency Limit of Crystal Impedance Meters", Engineering Report No. E-1170, U.S. Army Signal Engineering Laboratories, Signal Corps Task No. 8678, 31 January 1956.

8. Pochmerski, D., "VHF C.I. Meter AN/TSM-15", a paper presented at the 11th Annual Frequency Control Symposium, 9 May 1957.

9. Gruen, H. E., "Development of a Packet Oscillator Series", Final Report, Contract No. AF 33(616)-2125, Call No. 11A, Armour Research Foundation, 15 February 1956, or see SUPPLEMENTAL BIBLIOGRAPHY, Item No. 3, Paragraphs I-562 to I-568.

APPENDIX

III

SUPPLEMENTAL BIBLIOGRAPHY

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1. Heising, R., "Quartz Crystals for Electrical Circuits", 2nd Printing, Chapter XII Section 12.9 and Chapter XV, D. Van Nostrand Company, Inc., New York, N. Y., 1947.

2. Edson, W. A., "Vacuum Tube Oscillators", Chapter IX, John Wiley and Sons, Inc., New York, N. Y., 1953.

3. Buchanan, J. P., "Handbook of Piezoelectric Crystals for Radio Equipment Designers", Section I, Paragraphs I-376 to I-437 and I-562 to I-568, WADC Technical Report 56-156, Philco Corporation, Contract No. AF 33(616)-2453, WADC, ARDC, USAF, Wright-Patterson Air Force Base, Ohio, Oct., 1956.

4. Williams, E. K. and Marsh, A. W., "Harmonic Mode Quartz Crystals and Associated Oscillator Circuits for the 40 - 50 mc Range", TRE Technical Note No. 99, Telecommunications Research Establishment, Gt. Malvern, Worc., Great Britain.

5. Venn, D. A., "Current Status of Quartz Crystal Units and Circuitry for Frequency Control", NRL Report No. 4140, Radio Techniques Branch, Radio Division II, Naval Research Laboratory, Washington, D. C.

6. Butler, F., "Series Resonant Crystal Oscillators", Wireless Engineer, Vol. 23, June, 1946, pp. 157-160.

7. Goldberg, H. and Crosby, E. L., Jr., "Series Mode Quartz Crystal Oscillator Circuits", Proc. N.E.C., Vol. 3, 1947, pp. 240-250.

8. Butler, F., "Cathode-Coupled Crystal Oscillators", Short Wave Magazine, Vol. 7, June, 1949, pp. 258-262.

9. Koerner, L. F., "Progress in Development of Test Oscillators for Crystal Units", Proc. IRE, Vol. 39, January, 1951, pp. 15-26.

10. Fair, I. E., "Piezoelectric Crystals in Oscillators Circuits", Bell System Technical Journal, Vol. 24, April, 1945, pp. 161-251.

11. Gerber, E.A., "A Review of Methods for Measuring the Constants of Piezoelectric Vibrators", Proc., IRE, Vol. 41, September, 1953, pp. 1103-1112.

12. Gerber, E.A., "Quartz-Crystal Measurement at 10 to 180 Megacycles", Proc., Ire, Vol. 40, January, 1952, pp. 36-40.